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NUMERICAL SIMULATION OF SWEPT-WING FLOWS

A Progress Report for

Graduate Program in Aeronautics

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ABSTRACT

This progress report describes our efforts to computationally model the transition process characteristic of flows over swept wings. Specifically, the crossflow instability and crossflow/T-S wave interactions are analyzed through the numerical solution of the full three-dimensional Navier-Stokes equations including unsteadiness, curvature, and sweep. This approach is chosen because of the complexity of the problem and because it appears that linear stability theory is insufficient to explain the discrepancies between different experiments and between theory and experiments (e.g., steady vs. unsteady, interactions, . . .). The leading-edge region of a swept wing is considered in a three-dimensional *spatial* simulation with random disturbances as the initial conditions.

An ultimate goal of the work is the computational modeling of the receptivity problem for the swept wing through the use of the same numerical techniques. Toward this end, as a parallel effort to the swept-wing computations mentioned in the first paragraph, we continue the computational modeling of the receptivity of the laminar boundary layer on a semi-infinite flat plate with an elliptic leading edge by a spatial simulation. The incompressible flow is simulated by solving the governing full Navier-Stokes equations in general curvilinear coordinates by a finite-difference method. First, the steady basic-state solution is obtained in a transient approach using spatially varying time steps. Then, small-amplitude time-harmonic oscillations of the freestream streamwise velocity or vorticity are applied as unsteady boundary conditions, and the governing equations are solved time-accurately to evaluate the spatial and temporal developments of the perturbation leading to instability waves (Tollmien-Schlichting waves) in the boundary layer. The effect of leading-edge radius on receptivity is determined.

The work has been and continues to be closely coordinated with the experimental program of Professor William Saric, also at Arizona State University, examining the same problems. Comparisons with the experiments at Arizona State University are necessary and an important integral part of this work.

Whenever appropriate, we will match our results from the spatial simulation with triple-deck theory. This is an important aspect of the work.

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1. INTRODUCTION

In this progress report, Section 2 contains a list of related experience and accomplishments. Section 3 contains a summary of the work using a spatial, full Navier-Stokes simulation to examine the crossflow instability on swept wings. Section 4 contains a summary of the work that uses a spatial, full Navier-Stokes simulation to determine the mechanisms of receptivity and the role of leading-edge radius. The personnel involved in this project are described in Section 5.

2. RELATED EXPERIENCE AND TECHNICAL ACCOMPLISHMENTS

In the past, 10 students were supervised, 19 publications were written, and 30 talks and lectures were given. The two students who are considered for the fellowship are two of the PhD students supervised.

Publications

1. "Wave Interactions in Swept-Wing Flows," H.L. Reed, *Phys. Fluids*, Vol. 30, No. 11, p. 3419, 1987.
2. "Stability of Three-Dimensional Boundary Layers," H.L. Reed and W.S. Saric, *Ann. Rev. Fluid Mech.*, Vol. 21, p. 235, 1989.
3. "The Effects of Streamwise Vortices on Transition in the Plane Channel," B.A. Singer, H.L. Reed, and J.H. Ferziger, *Physics of Fluids A*, 1, 12, 1960-71, 1989.
4. "Stability of Three-Dimensional Supersonic Boundary Layers," P. Balakumar and H.L. Reed, in press *Physics of Fluids A*, 1991.
5. "Stability and Transition of Three-Dimensional Flows," H.L. Reed and W.S. Saric, *Invited Paper*, in *Proceedings of the Tenth U.S. National Congress of Applied Mechanics*, ASME, New York, 1987.
6. "Stability of Three-Dimensional Boundary Layers," H.L. Reed, *Invited Paper*, SAE 871857, AEROTECH '87 (Aerospace Technology Conference and Exposition), Long Beach, Oct. 5-8, 1987.
7. "Stability and Transition of Three-Dimensional Boundary Layers," W.S. Saric and H.L. Reed, *Invited Paper*, AGARD CP-438, *Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition*, Cesme, Turkey, Oct. 1988.
8. "Report of Computational Group," H.L. Reed, in *Transition in Turbines*, NASA CP 2386, NASA Lewis Research Center, May 1984.
9. "Wave Interactions in Swept-Wing Flows," H.L. Reed, *AIAA Paper 84-1678*.
10. "An Analysis of Wave Interactions in Swept-Wing Flows," H.L. Reed, 2nd

IUTAM Symposium on *Laminar-Turbulent Transition*, ed. V.V. Kozlov and V. Ya Levchenko, Springer-Verlag, New York, 1985.

11. "Disturbance-Wave Interactions in Flows with Crossflow," H.L. Reed, *AIAA Paper 85-0494*.
12. "Three-Dimensional Stability of Boundary Layers," W.S. Saric and H.L. Reed, in *Perspectives in Turbulence Studies*, ed. H.U. Meier and P. Bradshaw, Springer-Verlag, New York, 1987.
13. "Supersonic/Hypersonic Laminar/Turbulent Transition," H.L. Reed, G.K. Stuckert, and P. Balakumar, *Invited Paper*, in *Developments in Mechanics*, Vol. 15, Proceedings of the 21st Midwestern Mechanics Conference, Aug. 13-16, 1989.
14. "Receptivity of the Boundary Layer on a Semi-Infinite Flat Plate with an Elliptic Leading Edge," N. Lin, H.L. Reed, and W.S. Saric, Arizona State University, ASU 90006, Sept. 1989.
15. "Stability of High-Speed Chemically Reacting and Three-Dimensional Boundary Layers," H.L. Reed, G.K. Stuckert, and P. Balakumar, 3rd IUTAM Symposium on *Laminar-Turbulent Transition*, ed. R. Michel and D. Arnal, Springer-Verlag, New York, 1990.
16. "Boundary-Layer Receptivity: Navier-Stokes Computations," H.L. Reed, N. Lin, and W.S. Saric, *Applied Mechanics Review*, Vol. 43, Number 5, Part 2, Page S175, May 1990.
17. "Stability Limits of Supersonic Three-Dimensional Boundary Layers," H.L. Reed, T. Haynes, and P. Balakumar, *AIAA Paper No. 90-1528*.
18. "Simulations of Boundary-Layer Receptivity," H.L. Reed, *AFOSR Meeting on Turbulence Structure and Control*, Columbus, April 1-3, 1991.
19. "Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, *Royal Aeronautical Society Conference on Boundary-Layer Transition and Control*, Cambridge UK, April 1991.

Presentations

1. "Boundary Layer Stability - Recent Developments," H.L. Reed, Seminar in Fluid Mechanics, Nov. 2, 1982, Stanford.
2. "An Analysis of Instabilities in Laminar Viscous Flows," H.L. Reed, *Invited Seminar* in Applied Mathematics, Sandia National Laboratories, Albuquerque, Aug. 3, 1983.
3. "Wave Interactions in Swept-Wing Flows," H.L. Reed, NASA/Langley Research Center, June 13, 1984.
4. "Wave Interactions in Swept-Wing Flows," H.L. Reed, *Invited Paper*, 21st Annual Meeting of the Society of Engineering Science, Inc., VPI&SU, Blacksburg, Oct. 15-17, 1984.

5. "Crossflow/Tollmien-Schlichting Interactions in Swept-Wing Flows," H.L. Reed, Bull. Amer. Phys. Soc., Vol. 29, No. 9, p. 1554, Nov. 1984.
6. "Disturbance-Wave Interactions in Flows with Crossflow," H.L. Reed, *Invited*, Fluid Mechanics Seminar, UC Berkeley, Feb. 28, 1985.
7. "Computational Simulation of Transition," H.L. Reed, ICASE Meeting of Stability Theory, NASA/Langley Research Center, Nov. 21, 1986.
8. "Stability and Transition of Three-Dimensional Flows," H.L. Reed and W.S. Saric, *Invited Seminar*, Princeton, Apr. 21, 1987.
9. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Lecture*, Univ Ore, Eugene, Nov. 6, 1987.
10. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Talk*, Naval Post Graduate School, Monterey, Feb. 18, 1988.
11. "Computational Simulation of Three-Dimensional Boundary-Layer Flows," H.L. Reed, *Invited Lecture*, Tohoku University, Sendai, Japan, Apr. 1988.
12. "Computational Simulation of Three-Dimensional Boundary-Layer Flows," H.L. Reed, *Invited Lecture*, Hokkaido University, Sapporo, Japan, Apr. 1988.
13. "Energy-Efficient Aircraft," H.L. Reed, *Invited Talk*, Society of Women Engineers, Notre Dame, Nov. 9, 1988.
14. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Talk*, IBM Lecture Series, Notre Dame, Nov. 9, 1988.
15. "A Shear-Adaptive Approach to Spatial Simulations of Transition," H. Haj-Hariri and H.L. Reed, Bull. Amer. Phys. Soc., Vol. 33, No. 10, Nov. 1988.
16. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Lecture*, University of Western Ontario, London, Canada, Nov. 23, 1988.
17. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Seminar*, Univ Houston, Mar. 2, 1989.
18. "Boundary-Layer Receptivity: Computations," N. Lin, H.L. Reed, and W.S. Saric, Bull. Amer. Phys. Soc., Vol. 34, No. 10, Nov. 1989.
19. "Boundary Layer Receptivity: Computations," N. Lin, H.L. Reed, and W.S. Saric, *Third International Congress of Fluid Mechanics*, Cairo, January 1990.
20. "Boundary-Layer Receptivity," H.L. Reed, *Invited Seminar*, Michigan Technological University, February 9, 1990.
21. "Boundary-Layer Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, *Invited Paper*, in *Applied Mechanics Review*, Vol. 43, Number 5, Page S175, May 1990.
22. "Stability Limits of Supersonic Three-Dimensional Boundary Layers," H.L. Reed, T. Haynes, and P. Balakumar, *AIAA 21st Fluid Dynamics*,

Plasmadynamics and Lasers Conference, AIAA Paper No. 90-1528, Seattle, June 18-20, 1990.

23. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, *Keynote Speaker, 22nd Turbulence Symposium, National Aerospace Laboratory, Tokyo, July 25-27, 1990.*
24. "Boundary-Layer Receptivity to Sound: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, *43th Meeting of the American Physical Society, Division of Fluid Dynamics, Cornell, Bulletin American Physical Society, Volume 35, Number 10, Page 2260, November 1990.*
25. "Crossflow Instability in Supersonic Flow," H.L. Reed and T.S. Haynes, *43th Meeting of the American Physical Society, Division of Fluid Dynamics, Cornell, Bulletin American Physical Society, Volume 35, Number 10, Page 2322, November 1990.*
26. "Spinning-Cone Computations," H.L. Reed and T.S. Haynes, *Invited Presentation, 4th NASP Transition Workshop, NASA/Langley Research Center, December 4, 1990.*
27. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, *Invited Seminar, University of Cincinnati, February 1, 1991.*
28. "Simulations of Boundary-Layer Receptivity," H.L. Reed, *AFOSR Meeting on Turbulence Structure and Control, Columbus, April 1-3, 1991.*
29. "Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, *Royal Aeronautical Society Conference on Boundary-Layer Transition and Control, Cambridge UK, April 1991.*
30. "Crossflow Calculations for Supersonic Swept Wings," H.L. Reed, *Invited Seminar, McDonnell-Douglas, St. Louis, May 13-14, 1991.*

Post Doctoral Associates

H. Haj-Hariri, "Spatial Simulation of Transition," completed Spring 1988.

P. Balakumar, "Stability of Three-Dimensional Supersonic Boundary Layers," completed Spring 1989.

E. Tuluszka-Sznitko, "Breakdown of Three-Dimensional Boundary Layers," completed Spring 1990.

Ph.D. Students

B.A. Singer, "Numerical Simulation Studies of Laminar-Turbulent Transition in the Plane Channel," completed Spring 1987.

N. Lin, "Boundary-Layer Receptivity," expected Summer 1992.

T. Buter, "Boundary-Layer Receptivity to Three-Dimensional Disturbances," expected Summer 1992.

R.S. Lin, "The Crossflow Instability in Swept-Wing Flows," expected Summer 1992.

MS Students

N. Lin, "Receptivity of the Boundary-Layer Flow over a Semi-Infinite Flat Plate with an Elliptic Leading Edge," completed Fall 1989.

T. Haynes, "Stability of Three-Dimensional Supersonic Boundary Layers," completed Summer 1991.

Undergraduate Students

T. Haynes, "Stability of Boundary-Layer Flows," completed Fall 1988.

G. Loring, "Secondary Instabilities in Three-Dimensional Boundary Layers," completed Summer 1989.

D. Fuciarelli, "Breakdown in Three-Dimensional Boundary Layers," expected Spring 1992.

The technical accomplishments thus far are documented in the publications listed above. A brief description follows.

"Wave Interactions in Swept-Wing Flows," H.L. Reed, *Phys. Fluids*, Vol. 30, No. 11, p. 3419, 1987. Secondary-instability theory for three-dimensional boundary layers is described. In particular, it is shown that the early crossflow experiments of Saric exhibited a resonance between the fundamental and the second harmonic.

"Stability of Three-Dimensional Boundary Layers," H.L. Reed and W.S. Saric, *Ann. Rev. Fluid Mech.*, Vol. 21, p. 235, 1989. The paper is a complete literature review of the area of three-dimensional boundary-layer stability and transition as of June 1988. It obviates the need to review the literature in this report.

"The Effects of Streamwise Vortices on Transition in the Plane Channel," B.A. Singer, H.L. Reed, and J.H. Ferziger, *Physics of Fluids A*, 1, 12, 1960-71, 1989. This paper shows why the experiments of Nishioka were unable to produce H-type breakdown predicted by theory. The value of the computations in examining the role of "freestream" disturbances in the flow is demonstrated.

"A Shear-Adaptive Solution of the Spatial Stability of Boundary Layers with Outflow Conditions," H. Haj-Hariri and H.L. Reed, in preparation. This work outlines the numerics and boundary conditions used in our spatial simulations of transition.

"Stability of Three-Dimensional Boundary Layers," H.L. Reed, *Invited Paper*, SAE 871857, AEROTECH '87 (Aerospace Technology Conference and Exposition), Long Beach, Oct. 5-8, 1987. Here our computational simulations of swept wing flows are described, with results presented for the basic state.

"Stability of Three-Dimensional Supersonic Boundary Layers," P. Balakumar and H.L. Reed, in press *Phys. Fluids A*. Provides the characteristics of

crossflow in supersonic flow.

"Receptivity of the Boundary Layer on a Semi-Infinite Flat Plate with an Elliptic Leading Edge," N. Lin, H.L. Reed, and W.S. Saric, Arizona State University Report CEAS 90006, Sept. 1989. This report demonstrates the feasibility of numerically studying the receptivity problem and establishes the platform upon which our receptivity studies are based. This work represents the first successful numerical treatment of the receptivity problem!

"Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, *Royal Aeronautical Society Conference on Boundary-Layer Transition and Control*, Cambridge UK, April 1991. This paper includes the effects of non-infinite Reynolds number curvature discontinuities.

3. CROSSFLOW INSTABILITY

Direct numerical simulations are playing an increasingly important role in the investigation of transition. In such simulations, the full Navier-Stokes equations are solved directly by employing numerical methods, such as finite-difference or spectral methods. This approach is widely applicable since it avoids many of the restrictions that usually have to be imposed in theoretical models. From recent developments, it is apparent that linear stability theory suffers from this; the discrepancies between theory and experiment (i.e. steady versus unsteady; the role of interactions; the role of roughness, curvature, and freestream disturbances) are currently unexplainable for crossflow. It appears that stability theory is not well-posed; predicted N-factors can range from small to large for a given configuration depending on the version of theory used [Refs. 1,2]. The questions posed above must be addressed by computational simulations.

In this approach, in contrast to linear stability theory, no restrictions with respect to the form or amplitude of the disturbances have to be imposed, because no linearizations or special assumptions concerning the disturbances have to be made. Furthermore, this approach allows the realistic treatment of the space-amplified disturbances and no assumptions have to be made concerning the basic flow (such as that the flow be parallel). The basic idea of this method is to disturb an established basic flow by forced, time-dependent perturbations. Then the reaction of this flow, that is, the temporal and spatial development of the perturbations, is determined by the numerical solution of the complete Navier-Stokes equations.

The principal goal of the current research is therefore the *spatial* simulation of the process of laminar-turbulent transition in the leading-edge region of an infinitely long, swept wing. The existence of such a method will provide a tool which will enable computation to complement experimental contributions to further the understanding of the physics of these flows and, ultimately, will provide a tool for the prediction and modeling of these flows. This is an ambitious goal.

3.1 DESCRIPTION OF THE COMPUTATIONS

The object of this study is to investigate the crossflow instability on an infinite-span, 45° swept wing. The model wing consists of a 6:1 semi-elliptical nose followed by a flat plate. The 3-D unsteady incompressible Navier-Stokes equations are discretized by

a Fourier-spectral/finite-difference scheme. Near the leading edge, low-amplitude, steady blowing and suction is introduced on the wall surface to provide the initial disturbance for stationary crossflow. We have succeeded in observing the stationary, co-rotating structure.

3.1.1 BASIC STATE

We obtain the basic state by numerically solving the steady Navier-Stokes equations subject to the appropriate boundary conditions. The Reynolds number based on the freestream velocity (10 m/sec), reference length (0.1 m), and kinematic viscosity (0.15 cm²/sec) is $Re = 6.67 \times 10^4$. The essential features of the numerical scheme include the following:

- The equations are in primitive-variable form.
- A staggered grid (192 X 96 in x and y) is used [Figure 1].
- A 2nd-order finite-difference scheme is used.
- The momentum equations are solved by a line-iteration method and an under-relaxation factor is introduced for spatially varying time steps.
- An extra potential function is solved to correct the velocity field such that the continuity condition is satisfied at all intermediate iterative steps.
- The pressure Poisson equation is solved by a 5-level multigrid method.

Figure 2 shows the solution vectors in the x-y plane. Figure 3 shows the pressure distribution along the wall surface. Figure 4 gives more detail of the pressure distribution near the leading edge. About 50% of the elliptical leading edge is within the favorable pressure-gradient region. It is in this region that crossflow vortices will grow strongly. Finally, Figure 5 shows typical boundary-layer velocity profiles in both the local-inviscid and crossflow directions.

3.1.2 3-D UNSTEADY CALCULATIONS

For the infinite swept wing, we assume periodic boundary conditions in the spanwise direction (parallel to the leading edge). Our numerical scheme uses a Fourier spectral method in the spanwise direction, a Crank-Nicolson method in time, and a finite-

difference method in the other two coordinate directions. All dependent variables are in complex form. Thus far, for code validation purposes, we have used only 4 Fourier modes in the spanwise direction. An FFT is used to transfer information between the spectral domain and the physical domain.

Our first results have been for stationary crossflow vortices. Near the leading edge, low-amplitude steady blowing and suction is introduced on the wall to simulate surface roughness, and thus provide the initial disturbances [Figure 6]. The spanwise wavelength is chosen based on linear stability analysis. For this configuration, we set $\lambda = 3.24$ mm, which is locally the most unstable mode at the location 0.97 cm downstream from the leading edge.

From our numerical solutions, the field of disturbance velocities (v' , w') in the y-z plane is plotted in Figure 7. Note that w' is in the local crossflow direction, while z is in the spanwise direction. Our computational solutions reveal that within each wavelength, the disturbances alone (without the basic state) take the form of two counter-rotating vortices.

The basic-state velocities V and W have been added to v' and w' . Note again that W is the projection of the total steady velocity in the crossflow direction. We no longer observe one pair of counter-rotating vortices per wavelength, but instead only a single vortex can be observed in the boundary layer (the co-rotating crossflow vortices) [Figure 8]. Figures 9 and 10 show the resulting deformation to the streamwise component of velocity due to the presence of the crossflow.

4. RECEPTIVITY

Receptivity, the process by which external disturbances lead to instabilities in shear flows, plays a vital role in the transition from laminar to turbulent flow. The importance of receptivity in prediction, modelling and control of transition has been recognized (Ref. 3,4) and can not be overemphasized. Substantial progress has been made in investigating receptivity of boundary layers. Discussions of recent developments in boundary-layer receptivity theory may be found in Goldstein et al. (Ref. 5) and Kerschen (Ref. 6). A detailed review of some experiments on receptivity are presented in Nishioka and Morkovin (Ref. 7).

In the prediction of boundary-layer receptivity to freestream long-wavelength disturbances, theoretical investigations based on high-Reynolds-number asymptotic methods have identified that the conversion of freestream disturbances to TS instability waves takes place in the boundary layer where the mean flow exhibits rapid local variations in the streamwise direction (Ref. 6,8,9,10). The discussions here concentrate on receptivity to sound in the leading-edge region and at the ellipse-flat-plate juncture (Ref. 5,8,9).

A few experiments, using flat plates with elliptic leading edges, have been done on boundary-layer receptivity to freestream sound (Ref. 11,12,13,14). In Leehey et al. (Ref. 12) a leading edge with $AR=6$ was used. Acoustic receptivity for their flat plate was reduced from order one to essentially nothing after tipping the plate to obtain a zero mean-pressure gradient. Results of Wlezien and Parekh (Ref. 13) using $AR=6$ and $AR=24$ (on a solid plate) and Saric et al. (Ref. 14) using $AR=67$ (without roughness elements on a highly-polished plate) indicate that a sharper leading edge is less receptive to a plane sound wave. In these later experiments (Ref. 13,14), mean pressure gradients are effectively zero and junctures between the leading edge and the flat plate are smoothed by a filler.

In terms of the computational modelling of the boundary-layer receptivity to long-wavelength acoustic waves, Kachanov et al. (Ref. 15) solved the incompressible flow over an infinitely thin flat plate, using the Navier-Stokes equations linearized for small disturbances. A freestream vortical disturbance and a transverse acoustic wave across the leading edge were considered. Murdock studied the receptivity to a plane parallel sound wave of the boundary layer over a flat plate with no thickness (Ref. 16) and parabolic bodies (Ref. 17), solving the parabolized Navier-Stokes equations. Receptivity was found

to occur near the leading edge. A sharper leading edge (smaller nose radius) was reported to be more receptive; it should be noted that these bodies have favorable pressure gradients everywhere. Gatski et al. (Ref. 18) solved the full Navier-Stokes equations for flow over an infinitely thin, semi-infinite flat plate. No clear development of the TS wave due to freestream oscillations was reported.

These results from experiments, computations and theories indicate that, differences in not only parameters such as F and Re , but also details of leading-edge curvature, local and freestream steady/unsteady pressure gradients can affect receptivity greatly. It is apparent that the leading-edge region does provide length scales necessary for the conversion of freestream disturbances to instability waves, and thus is a focal region of receptivity. In an attempt to investigate receptivity mechanisms to freestream disturbances, we have developed a numerical code to compute the unsteady incompressible flow over a semi-infinite flat plate with an elliptic leading edge solving the full unsteady Navier-Stokes equations (Ref. 19). The main feature of this work is the use of a body-fitted curvilinear coordinate system to calculate the leading-edge region with fine resolution. We consider time-harmonic small-amplitude oscillations about the steady freestream, which closely simulate a travelling sound wave in the incompressible limit. The results of this computational work should provide an independent verification and complement theoretical and experimental studies on acoustic receptivity.

4.1 NUMERICAL FORMULATION.

The governing equations are the two-dimensional unsteady incompressible Navier-Stokes equations with vorticity and stream function as dependent variables. A C-type orthogonal grid is generated around the leading edge and the flat plate (Fig. 11). The boundary conditions are the usual no-slip and no-penetration conditions at the wall, inviscid freestream velocities at the farfield boundary, and nonreflective numerical boundary conditions downstream (Ref. 20). The equations and boundary conditions are written in general curvilinear coordinates and discretized in space and time, using second-order accurate finite differences. No artificial diffusion is applied, yet the implicit iterative method used is found to be robust and stable with the use of reasonably small time steps. Further details of the numerical formulation may be found in Lin (Ref. 19).

First, a basic-state solution is computed by solving the governing equations for steady, incompressible flow with a uniform freestream, using a transient approach and spatially varying time steps. Then the steady flow is disturbed by applying forced

perturbations about the steady basic flow at the freestream as unsteady boundary conditions. The resulting unsteady flow and the temporal and spatial development of the perturbations are calculated by solving the unsteady governing equations time accurately. Recent results of our computations pertaining to receptivity to freestream acoustic waves are reported next.

4.2 STEADY - STATE SOLUTIONS

Steady-state solutions are obtained for three different values of the aspect ratio (AR) of the semi-ellipse, i.e. $AR = 3, 6$ and 9 . In all cases, the Reynolds number, based on half-thickness of the flat plate or the minor radius of the semi-ellipse L and the freestream velocity U , is chosen to be 2400 . In modelling the semi-infinite flat plate the downstream computational boundary is located such that the branch I of the neutral stability curve for Blasius flow (according to linear parallel theory) is well within the computational domain. The farfield computational boundary is located at about 25 to 30 Blasius-boundary-layer thicknesses at the downstream region. The grid-point distribution in the streamwise direction is determined not only to ensure high resolution of the leading-edge region where the curvature is changing rapidly, and at the ellipse-flat-plate juncture, but also to have at least 10 to 20 grid points in one expected TS wavelength for unsteady calculations. The stretching in the normal direction is done to pack more grid points near the wall to resolve the boundary layer and the Stokes viscous layer of the unsteady solution. Extensive numerical studies have been made to insure the adequacy of grid resolution and computational boundary locations.

Typical steady-state solutions are presented in Figures 12-15. The wall vorticity (Fig. 12-13) differs appreciably from that of the Blasius solution near the leading edge. The sharper leading edges exhibit a peak vorticity closer to the singular behavior of the Blasius vorticity, as expected. Velocity vector profiles, not shown here, accordingly differ from Blasius profiles, having overshoots above the freestream velocity at the leading-edge region. The surface pressure coefficient distributions (Fig. 14) of the sharper leading edges have smaller pressure minima after acceleration around the leading edge, hence smaller magnitudes of adverse pressure gradient in the pressure-recovery region. After this recovery, the pressure coefficient is very close to the inviscid solution, with a very small and almost constant adverse pressure gradient downstream. The square of the displacement thickness, δ^2 (Fig. 15), varies linearly with x , after some distance from the leading edge. The virtual leading edges are located upstream of the actual ones, due to rapid thickening of the boundary layer in the pressure-recovery region.

4.3 UNSTEADY SOLUTIONS

Results of unsteady calculations, carried out at two different values of the nondimensional frequency parameter, i.e. $F=230$ and 110 , are presented here. Perturbations that eventually develop in the flow will vary at constant forcing frequency (except at the developing wavefront where we can observe small high-frequency components), thus following $F=\text{constant}$ lines with downstream distance or $Re\delta^*$ (Fig. 16). The amplitude of the freestream oscillations (or the amplitude of the sound wave, a) used in these results is either $10^{-4}U$ or $2 \times 10^{-4}U$. Test calculations have been done with the value of a as large as $10^{-3}U$ and the disturbance response in the boundary layer is found to vary linearly with a .

Typical results, for the $F=230$, $AR=3$ case, are shown in Figures 17-19. Temporal development of the disturbance quantities u' , v' and w' at a fixed location in the boundary layer is shown in Figure 17. The disturbances are sinusoidal in time at the forcing frequency except at times when the developing TS wavefront passes through. In Figure 18, we can observe the initial development of the disturbance wave near the leading-edge region and its subsequent propagation downstream. The wavelength is very close to the TS wavelength predicted by the linear stability theory. At the wavefront, dispersive behavior of the leading wave packet created during the start of the freestream forcing can be noticed, especially in the v' disturbance.

During the fourth period of forcing, the theoretical Stokes-wave solution is subtracted from the Navier-Stokes solution and the amplitude profiles of the remaining disturbance are obtained. These profiles are shown in Figure 19. The profiles gradually develop into typical TS-wave profiles after some distance from the leading-edge. Amplitude profiles are zero downstream of the TS wavefront, as expected. The magnitude of receptivity, as defined by the maximum amplitude of u' (of the TS wave only) in the boundary layer to the amplitude of the freestream sound, a , is found to be about 0.8, i.e. order one, for this $AR=3$ leading edge at $F=230$.

The effect of leading-edge curvature on receptivity is investigated by varying the AR of the semi-ellipse while keeping the thickness L (hence Re) the same. The amplitude of the TS wave is smaller for sharper leading edges. This can be seen clearly in surface plots of instantaneous streamwise disturbance velocity, u' , after 4 cycles of forcing and after subtracting the Stokes wave (Fig. 20-21). At $F=230$, the magnitude of receptivity is

found to be of order (10^{-1}) for the $AR=9$ leading edge. This magnitude is of the same order but approximately twice as large for the $AR=6$ plate. A sharper leading edge has a larger curvature at the nose, has a smaller (in magnitude) local adverse pressure gradient in the leading-edge region and also has a smaller magnitude of discontinuity in curvature at the ellipse-flat-plate juncture. It is a combination of these factors that may contribute to reduced receptivity.

As for the effect of frequency parameter F (for the same AR), a lower value of F is found to give a larger amplitude of u' at the region of genesis, i.e. near the juncture. This could be explained in terms of the relative matching of the TS wavelengths at two different values of F and the length scales of the leading-edge curvature. Farther downstream, the TS wave amplitude is smaller for a lower F since damping rates before the first neutral-stability point are stronger.

Asymptotic theories of Goldstein (Ref. 5,9), in comparison with experiments of Leehey et al. (Ref. 11), predicted that discontinuity in surface curvature at the juncture contributes more to order-one receptivity, while the disturbances inception due to leading-edge adjustment of the boundary layer (Ref. 8) have a much smaller contribution due to their rapid decay. In order to determine how much of the receptivity is being provided by the discontinuity in surface curvature, a portion of the surface at the juncture region of the $AR=6$ leading edge is replaced by a polynomial, making the curvature continuous everywhere. Figures 22-23 illustrate the surface curvature variation before and after this smoothing. The inherent change in the pressure gradient due to smoothing along the surface is small (Fig. 24) and an enlarged view of the pressure gradient is given in Figure 25. Then steady and unsteady results are obtained at $F=230$, using the same grid resolution and time-step size. The two solutions obtained with continuous and discontinuous curvature are compared in Figures 26 and 27. It is clear that discontinuous curvature enhances receptivity by about two fold.

The TS-wave amplitude with continuous curvature is still appreciable and very little change in streamwise phase of this TS wave, due to change of curvature, is observed. This might be due to the fact that the variation of curvature, though continuous, is still rapid enough (Fig. 23) in this region with peak adverse pressure gradient, to enhance receptivity. Moreover, a rapid growth of the boundary layer, the effect of which on receptivity is analyzed in theory (Ref. 8) using an infinitely thin plate, occurs right near this juncture for our calculations (Fig. 15). More calculations involving different variations of curvature, Re and F are necessary to verify mechanisms of receptivity in this region.

Figures 28 through 31 show color plots of disturbance stream-function contours after several cycles of forcing. A comparison of Figures 28, 29, and 31 ($AR = 3, 6$, and 9 , respectively) clearly shows the effect of leading-edge radius on disturbance amplitude in the boundary layer. Increasing aspect ratio is associated with lower T-S wave amplitudes. Even in the $AR = 9$ case (sharp), some evidence of a disturbance convecting from the leading edge is still apparent. Figures 29 and 30 clearly show the effect of the discontinuity in curvature for $AR = 6$. Smoothing the discontinuity (Figure 30) leads to lower T-S wave amplitudes downstream of the juncture. The pattern between the stagnation point and the juncture, though, is unchanged, indicating that both the juncture and the leading edge contribute to receptivity.

4.4 CONCLUSIONS

The receptivity of the laminar boundary layer over a semi-infinite flat plate at the leading-edge region is investigated by direct numerical solution of the full Navier-Stokes equations. The leading-edge curvature and finite thickness of the flat plate are included by using body-fitted coordinates. We are able to observe both temporal and spatial initial developments of the TS wave in the boundary layer due to time-harmonic oscillations of the freestream streamwise velocity.

The receptivity occurs in the leading-edge region where rapid adjustments of the basic flow exist. In this region the variation of curvature, the adjustment of the growing boundary layer, the discontinuity in surface curvature and the inherent local pressure gradients introduce length scales to the thin layer of oscillating vorticity imposed by the long-wavelength freestream disturbances. This leads to the development of a TS wave in the boundary layer and its propagation downstream.

In general, the quantitative measure of receptivity depends on the leading-edge radius of curvature, with sharper leading edges being less receptive to plane sound waves. The contribution from the discontinuity in curvature to receptivity is found to be substantial, making up almost 50 percent of the total receptivity for the $AR=6$ leading edge at $F=230$.

5. REFERENCES

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6. RESOURCES AND PERSONNEL

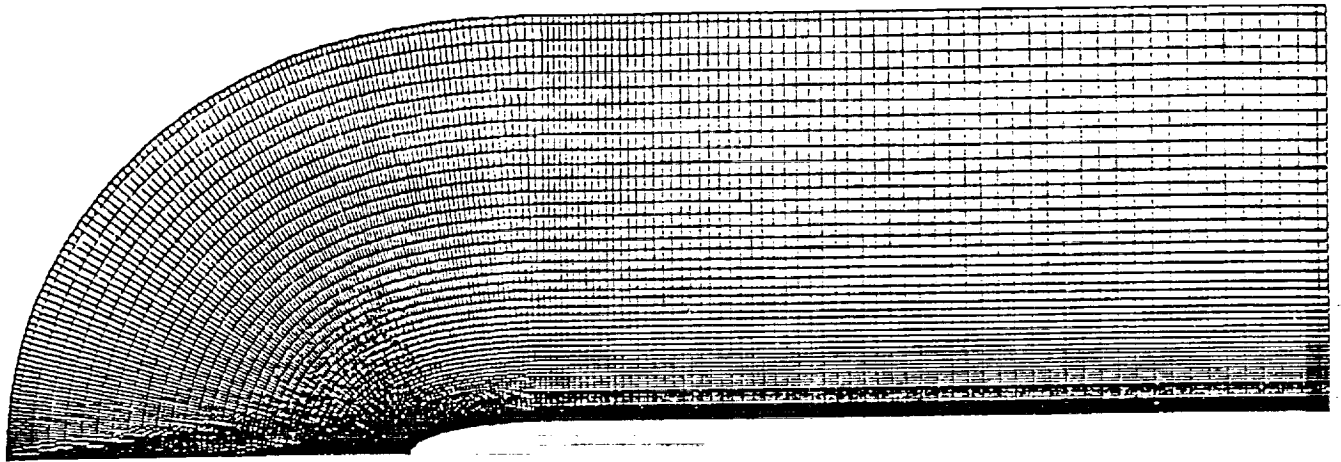
One of the principal strengths of our team at Arizona State University is its broad skills in analysis, computations, and experiments. We facilitate day-to-day communication between the computational work and the experimental work through two IRIS Graphics Workstations (3030 and 3130) and two DEC 5000 Workstations. The system, with state-of-the-art, real-time, three-dimensional, color-graphics software (PLOT3D), is equipped with an extensive multi-user and multi-task environment with twelve serial lines. Users are able to share the same data base or experimental information. This provides the heart of the interaction of the analytical, computational, and experimental research.

In addition to the super computers at NASA facilities and Princeton/NSF Consortium, the network includes access to the IBM 4341/VM and Harris/VS computers, the IBM 3090 Class VI machine, and the Cray XMP on campus as well as the MASSCOMP. The College of Engineering at ASU is currently also equipped with several VAX/780 and VAX/785 minicomputers exclusively for research purposes (each office and laboratory has a hard-wired RS232 interface). These minicomputers are excellent systems for program development. The IRIS and DEC machines can access all the features available in those minicomputers through the existing local area networking (Ethernet) on the campus. Furthermore, the system can communicate directly with NASA research facilities to share information through telephone couplings. The full array of computer capabilities from super-mini to super-super is in place for the research.

Ray-Sing Lin, a PhD student, and Nay Lin, a PhD student, are the two candidates for the Fellowship. Each will be spending one month of the summer of 1991 at Langley Research Center working on these and similar problems, interacting with NASA and ICASE personnel.

The principal investigator for this work is Helen L. Reed, Associate Professor of Mechanical and Aerospace Engineering. Professor Reed has spent the last ten years conducting theoretical and computational research on problems of boundary-layer stability specifically applied to the ACEE/LFC programs. She will also spend one month of the summer of 1991 at NASA/Langley Research Center. Her resume is attached as Appendix I.

7. FIGURES



NX=192. NY=96.

Figure 1

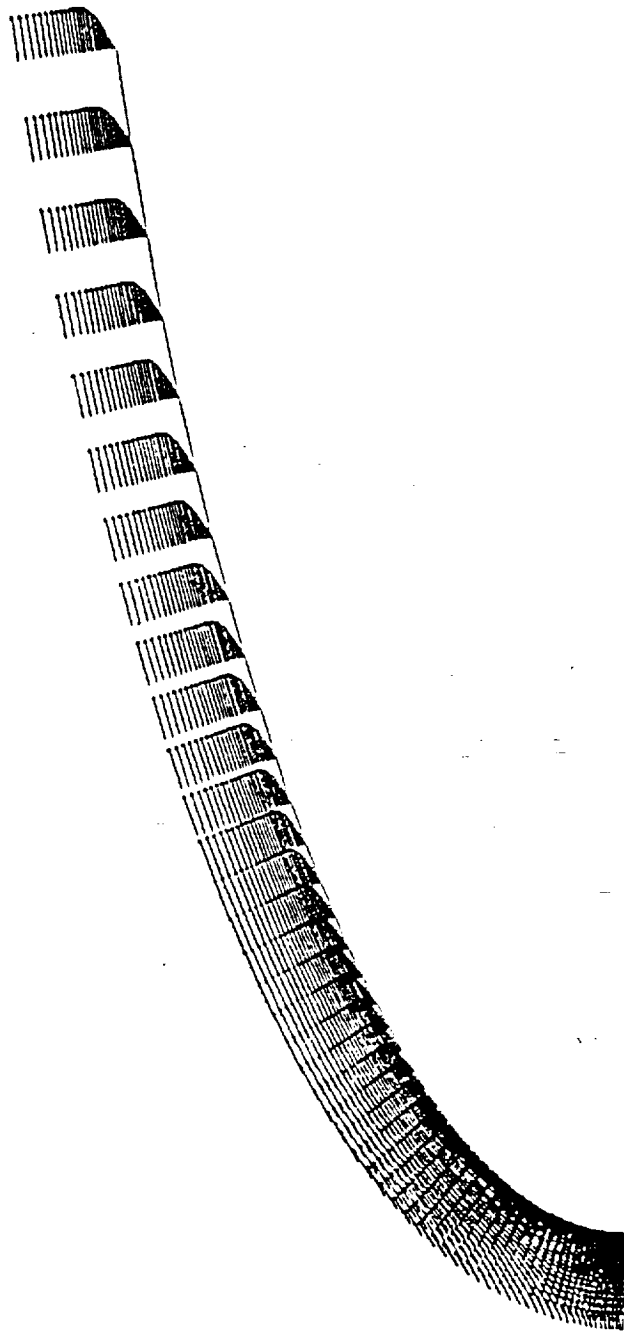


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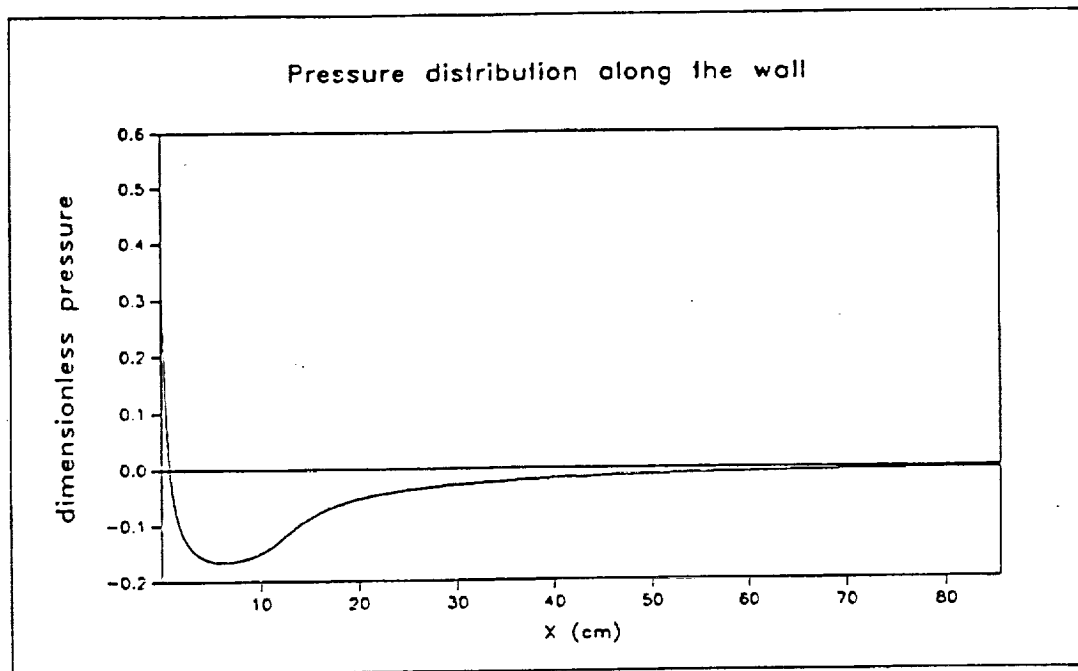


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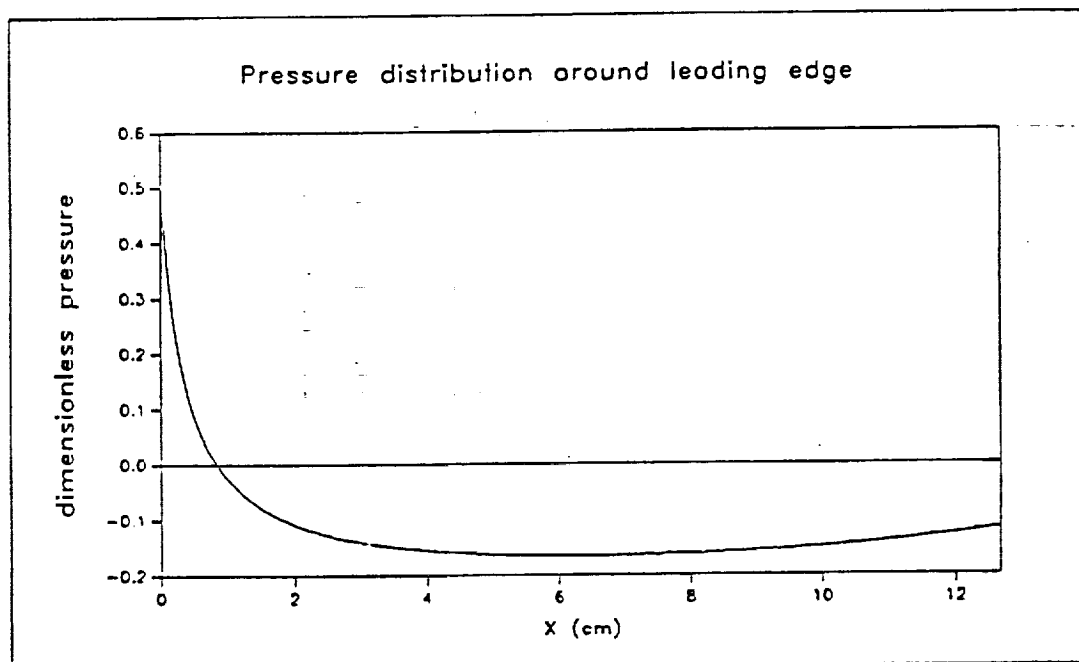


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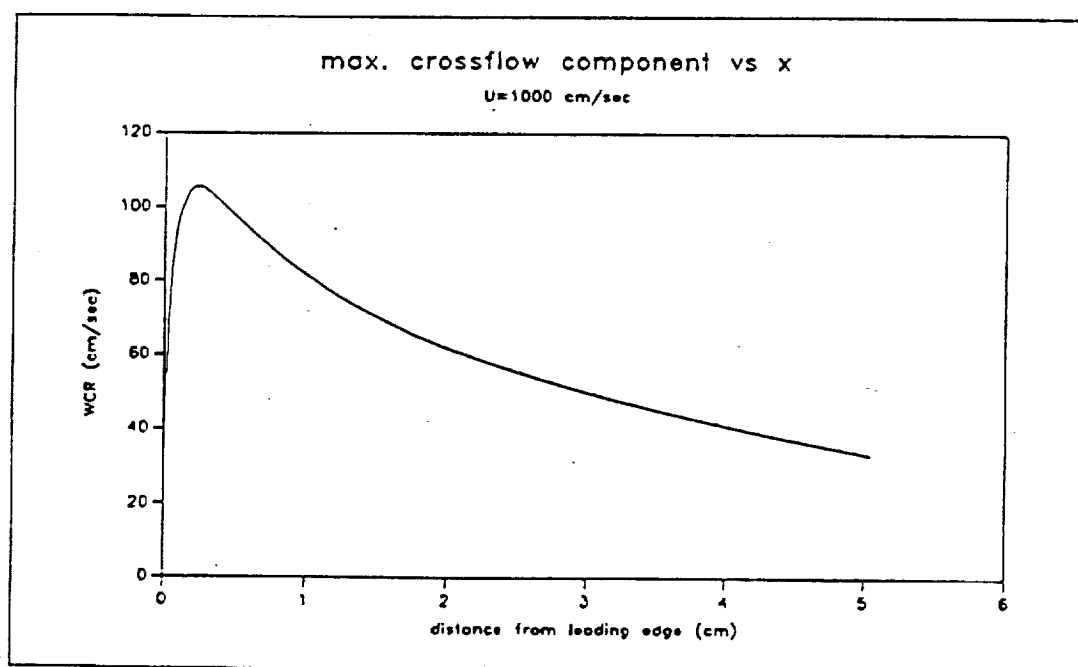
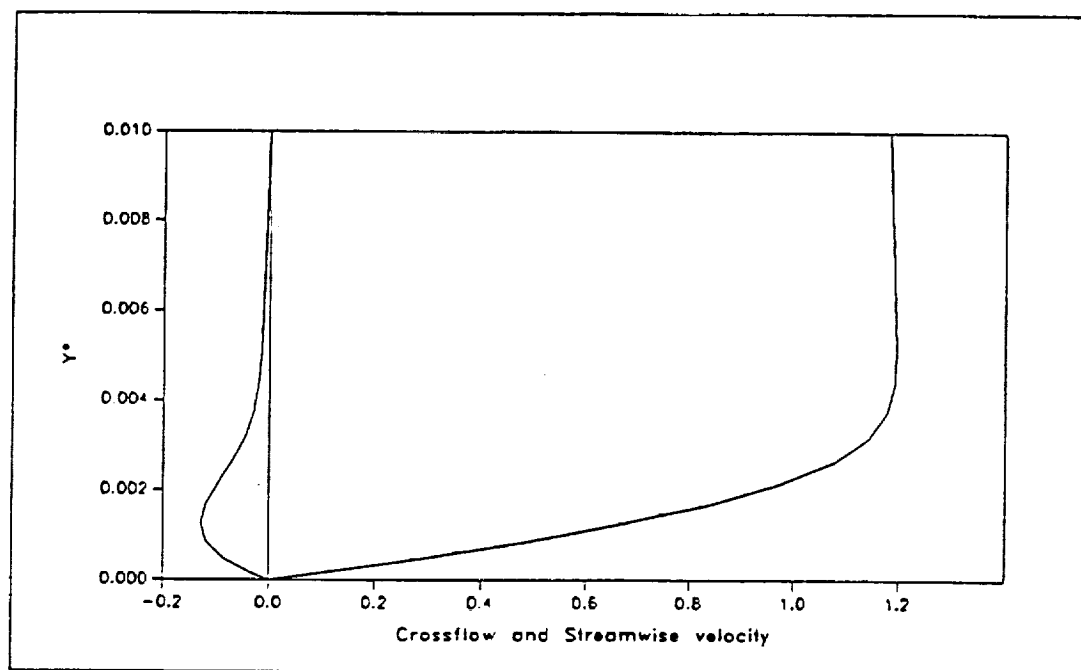


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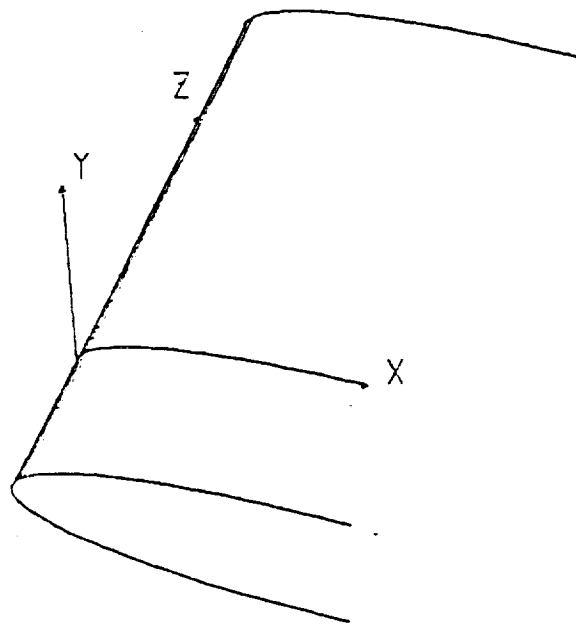


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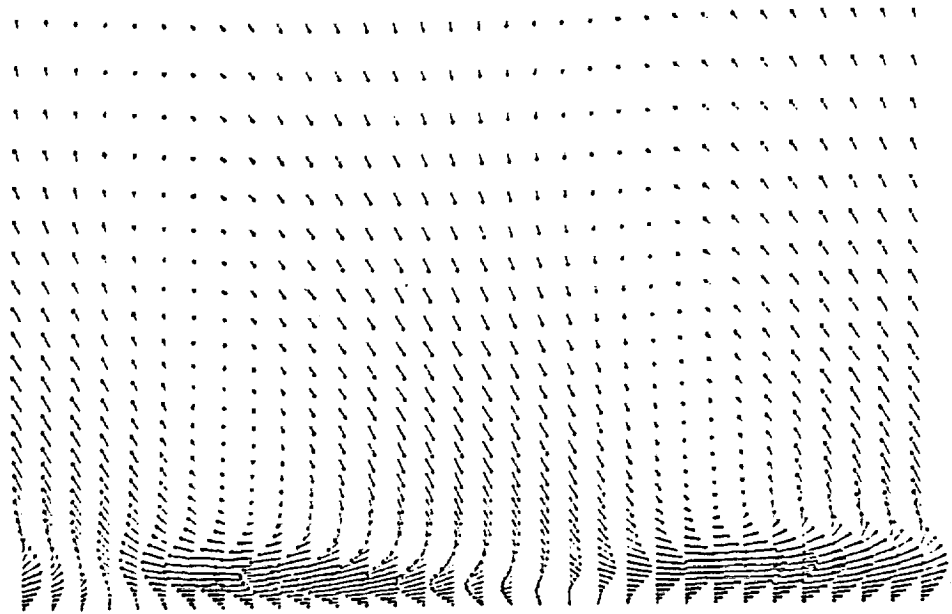


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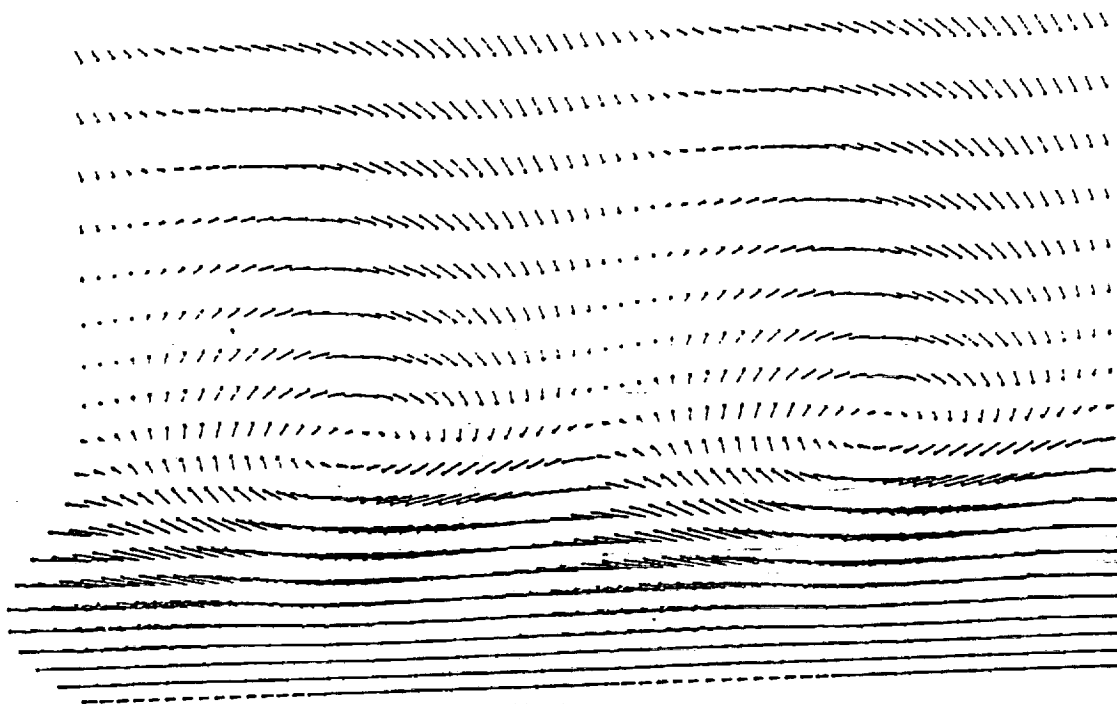
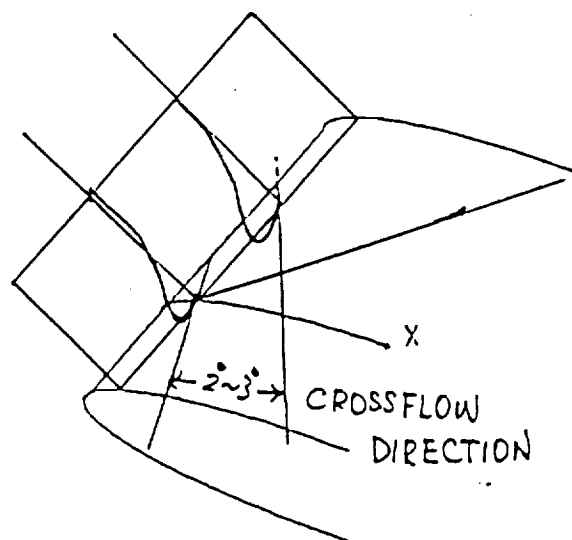


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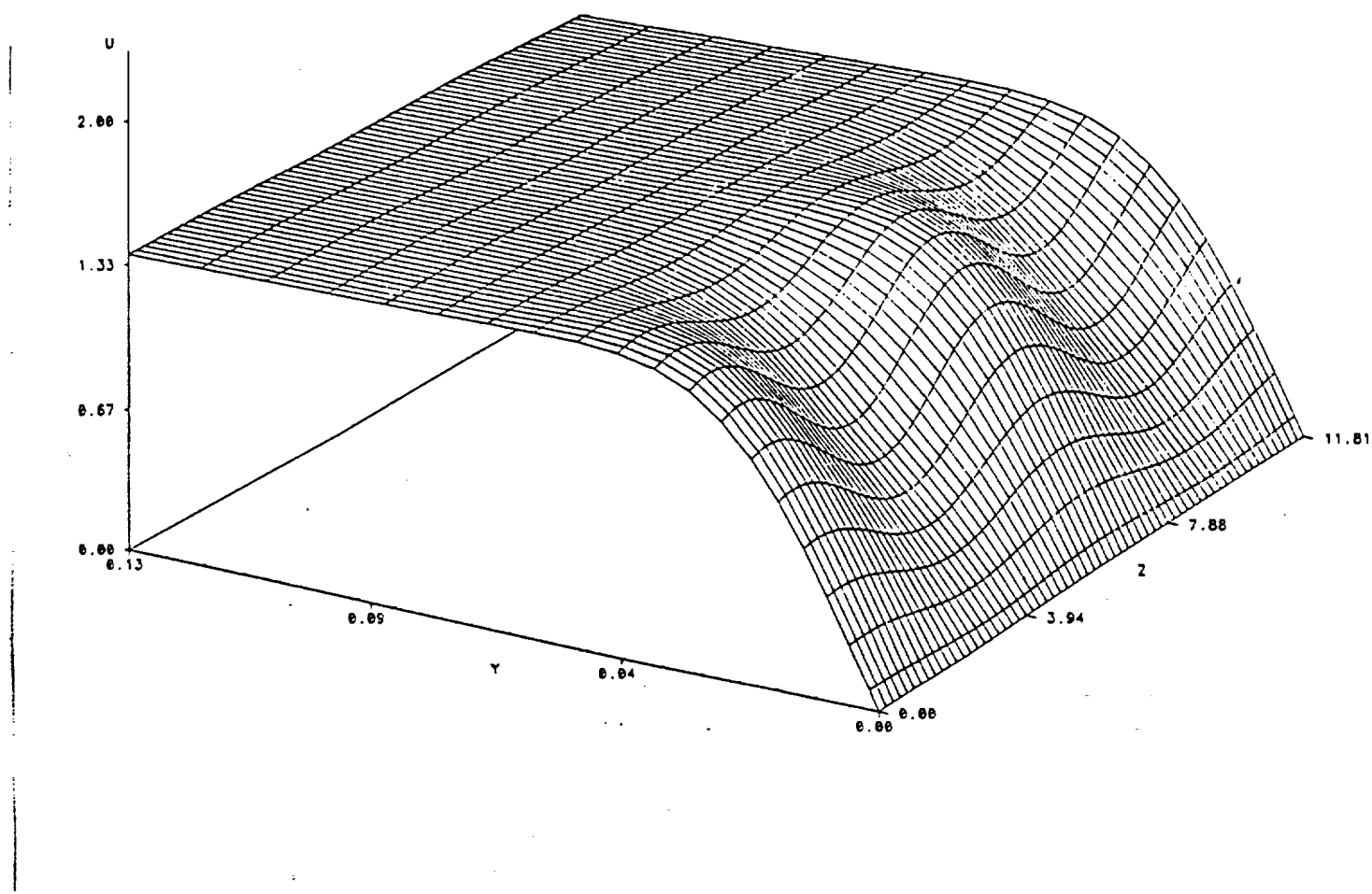


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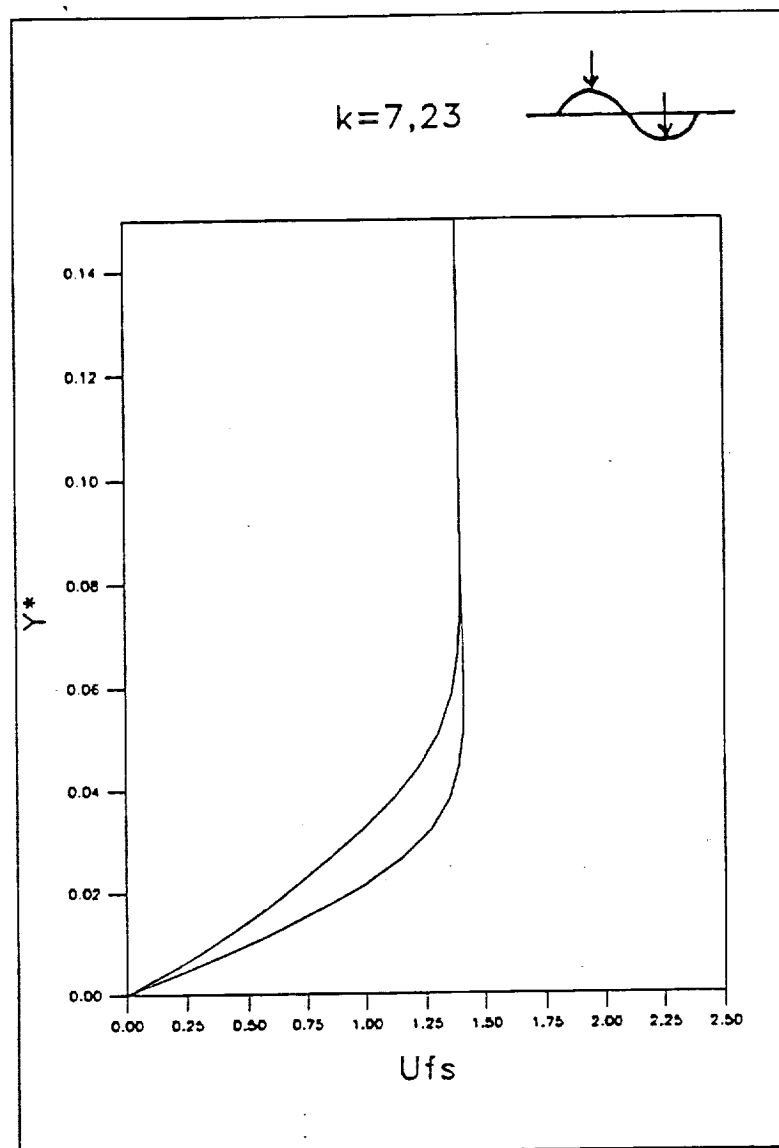


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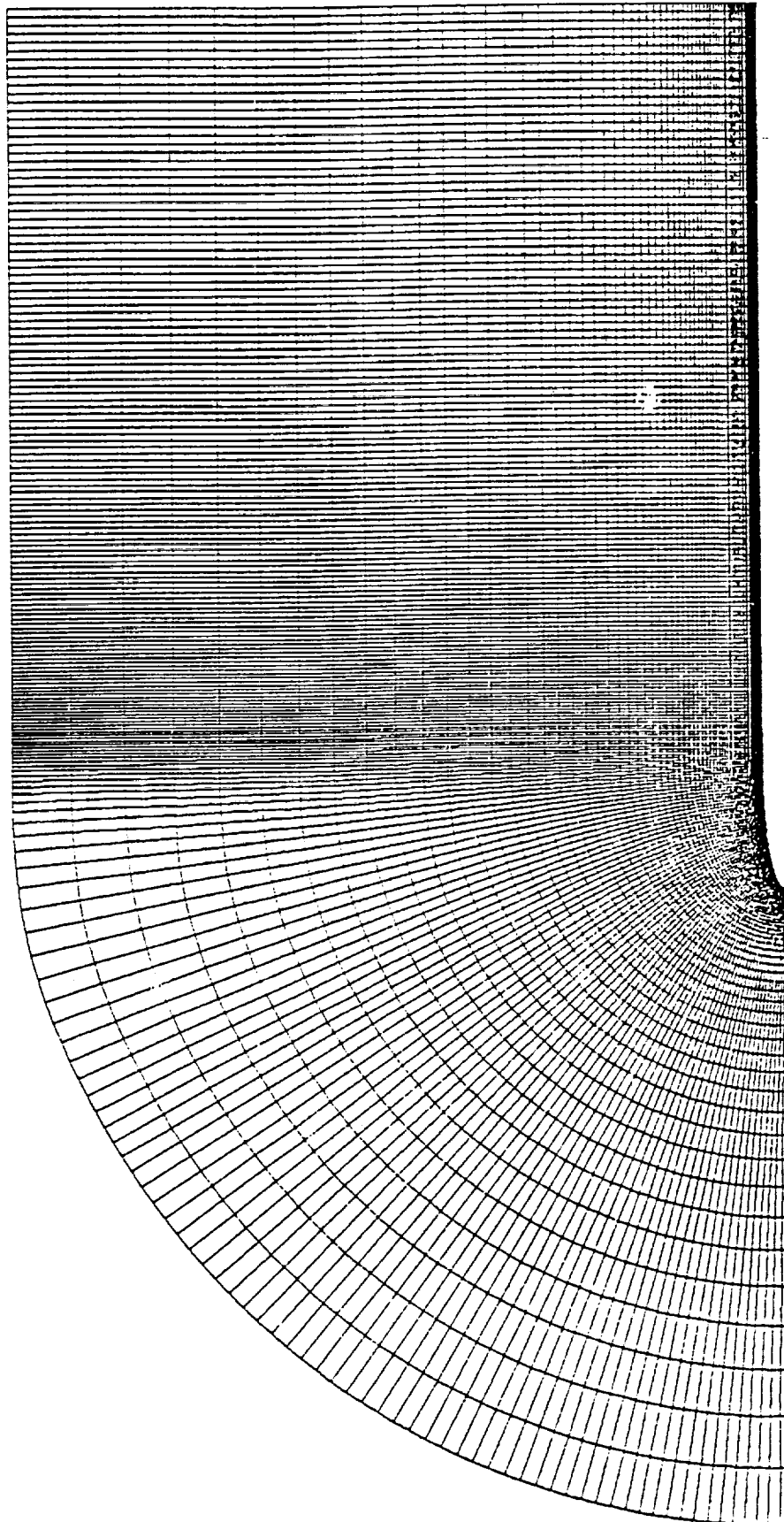


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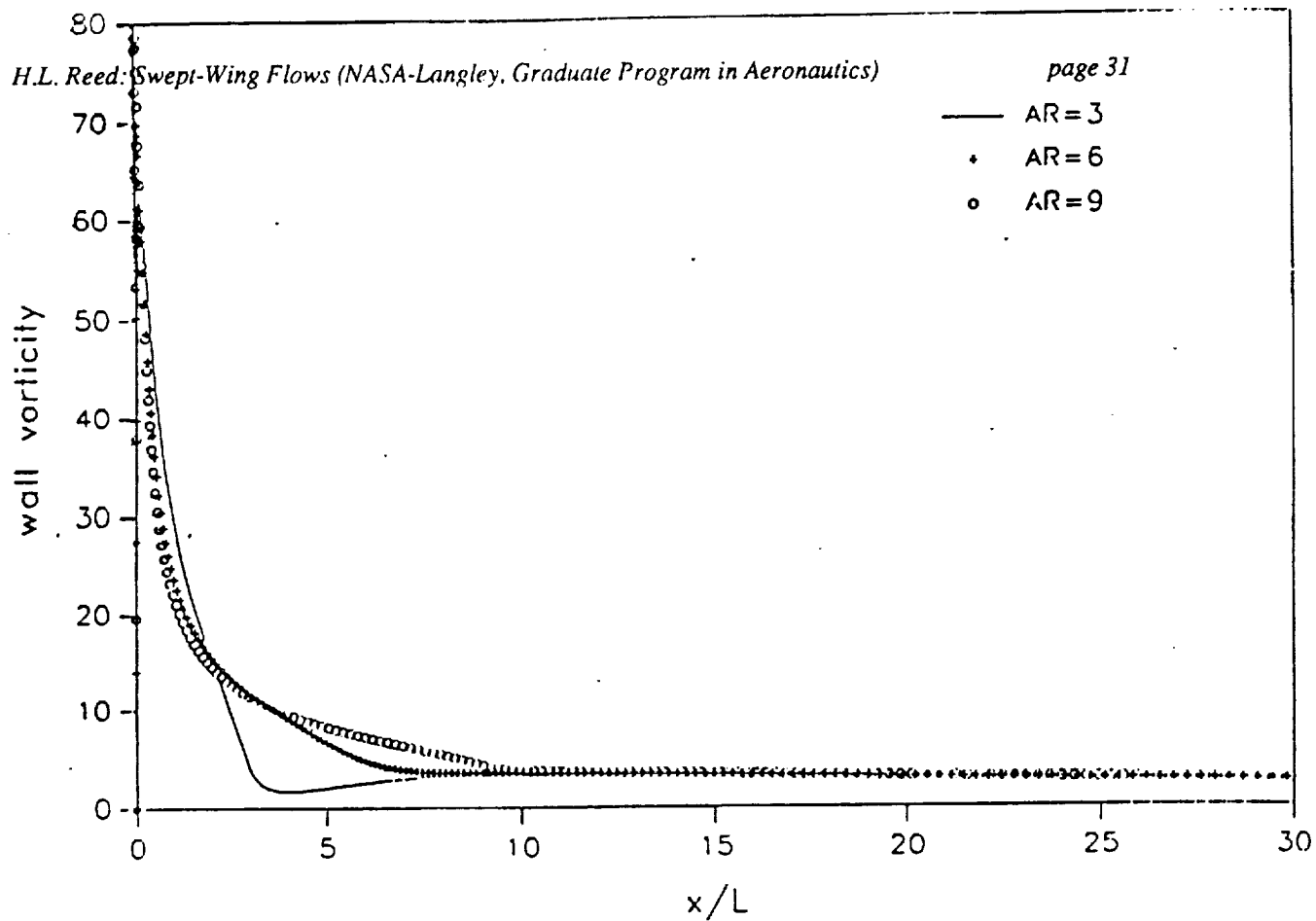


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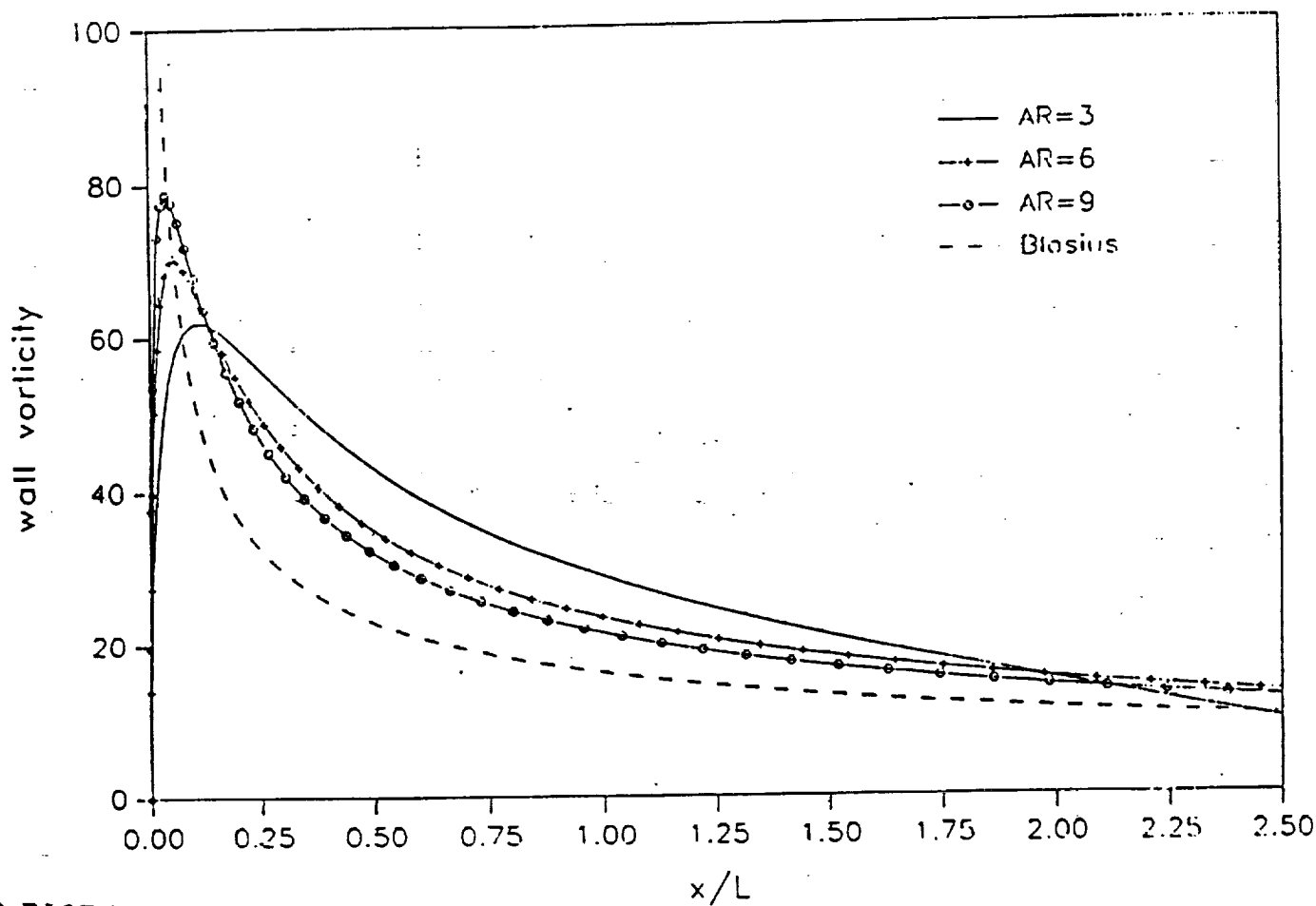


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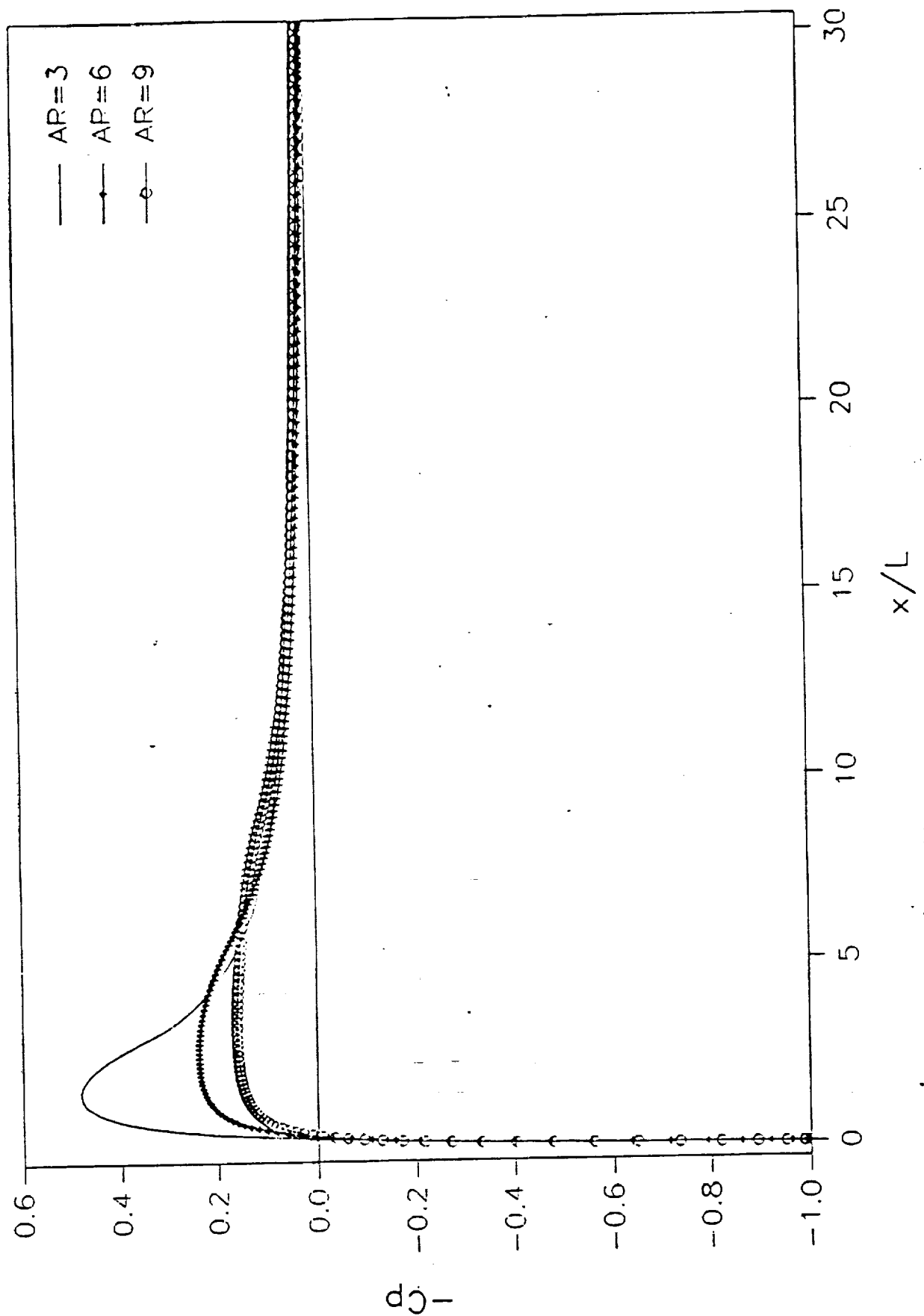


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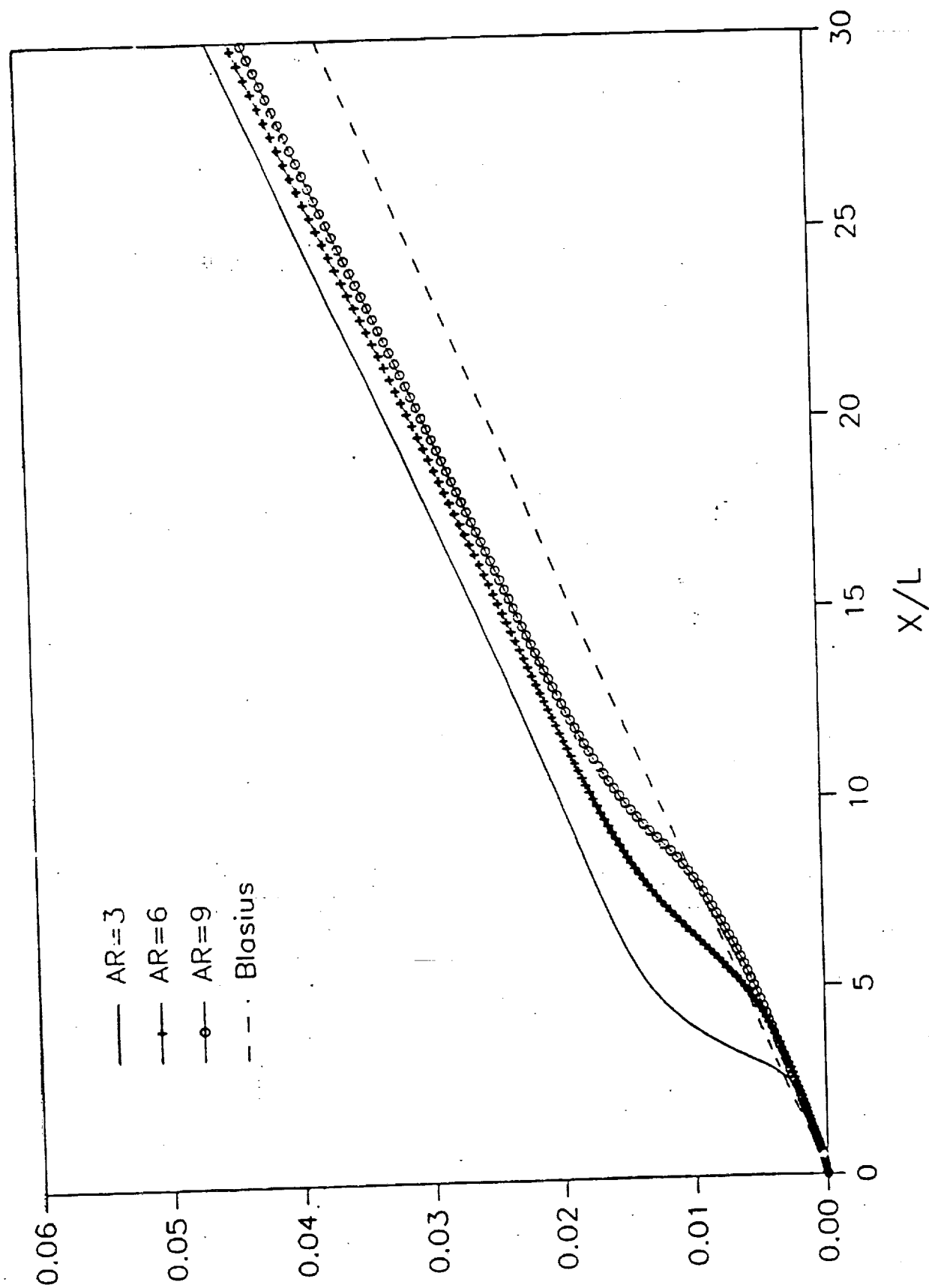


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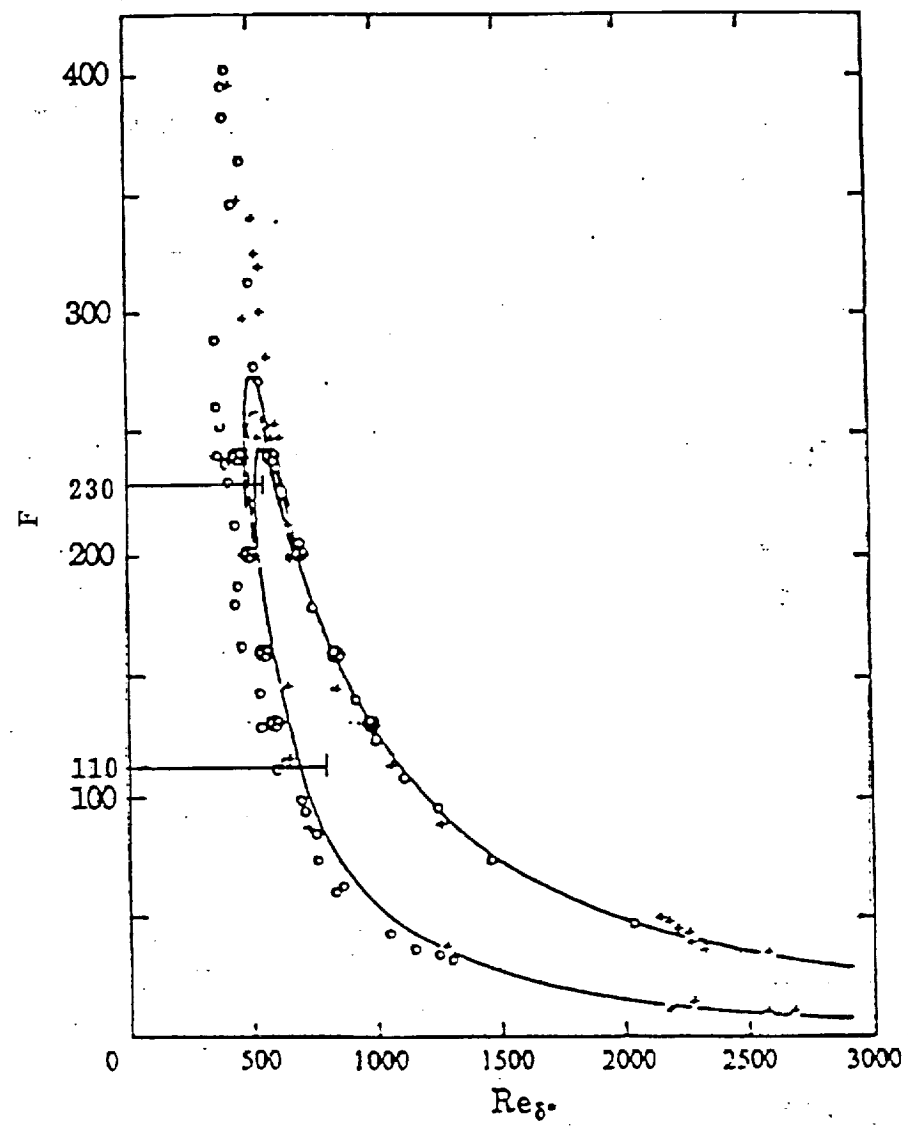


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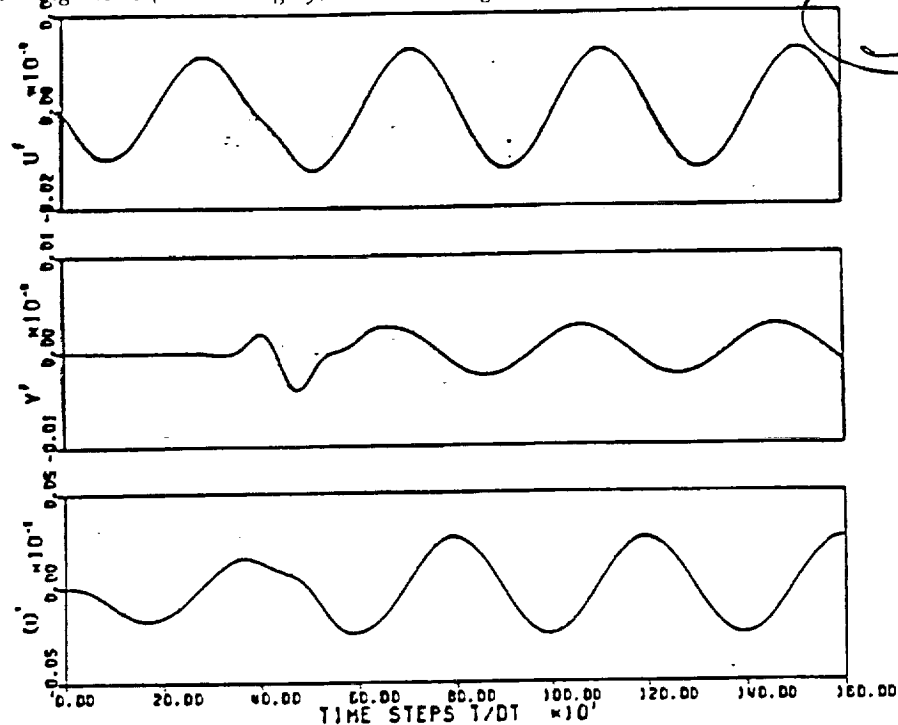


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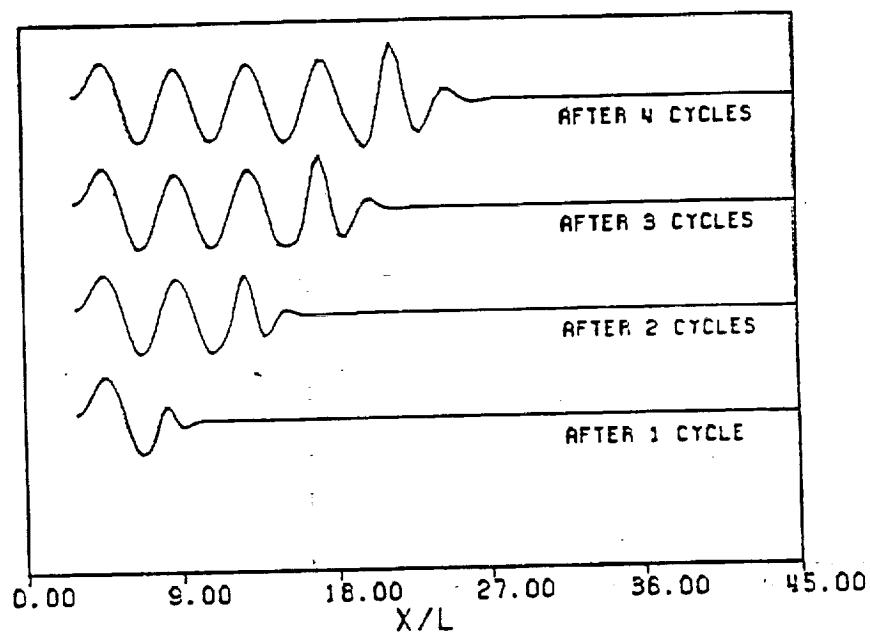


Figure 18

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AMPLITUDE PROFILES OF u' (AFTER STOKES WAVE IS SUBTRACTED)

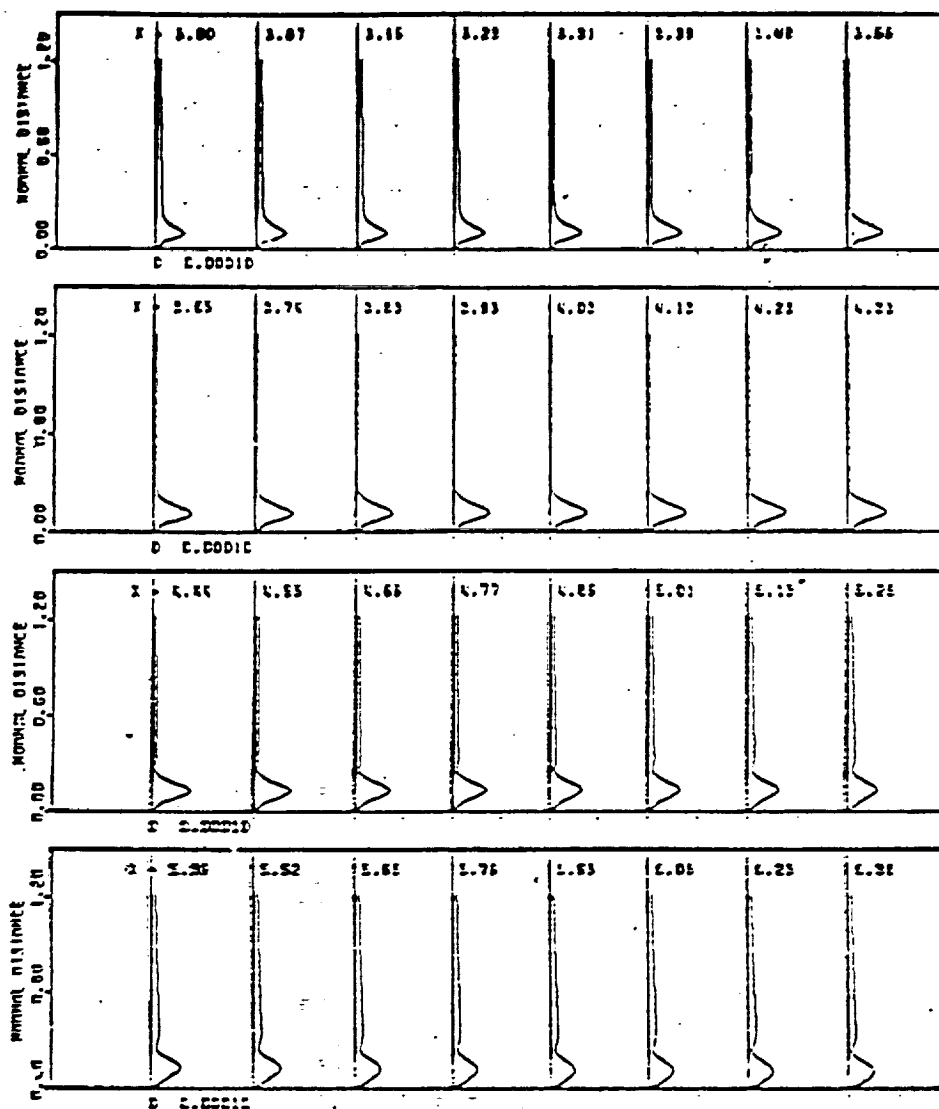


Figure 19

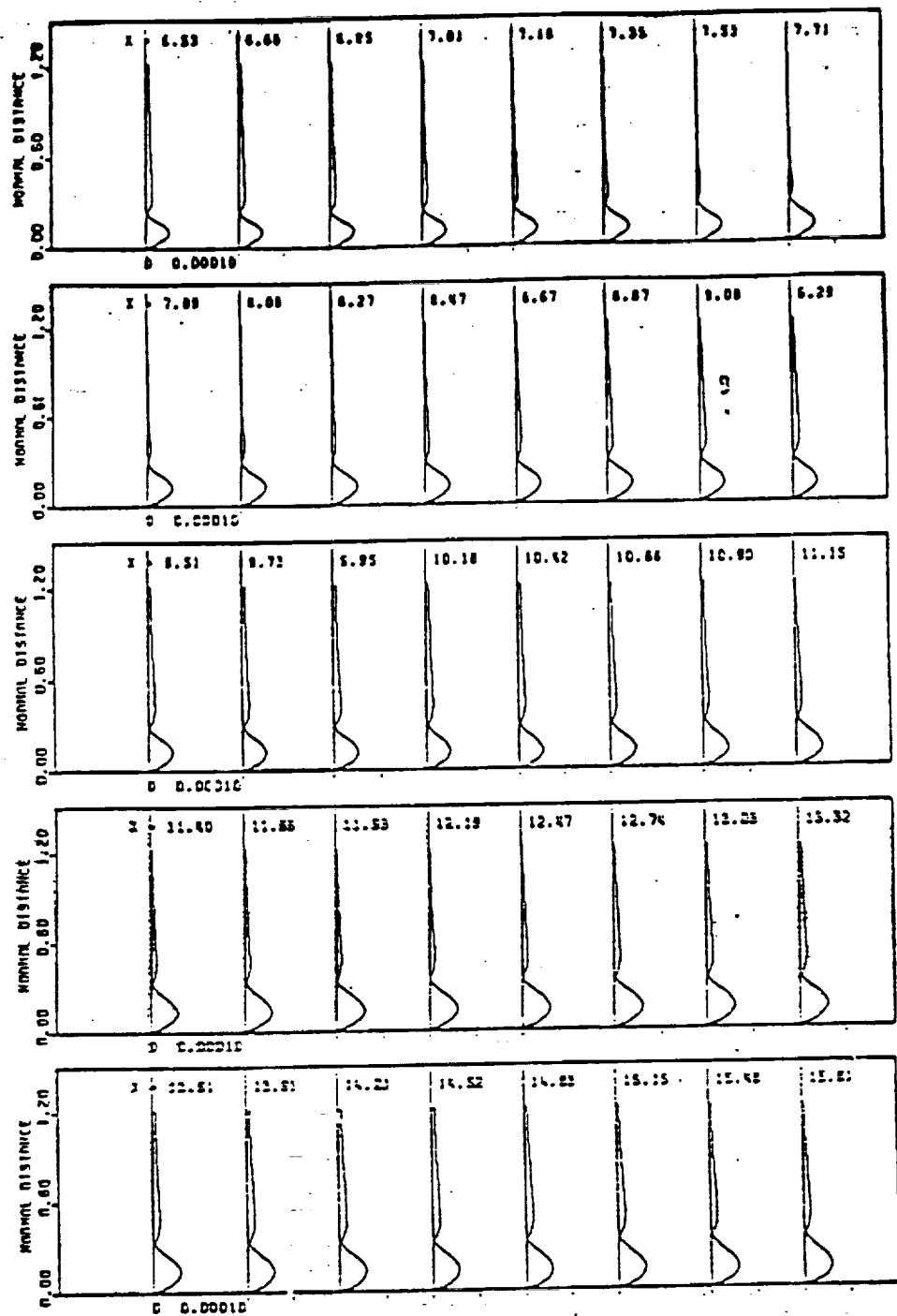
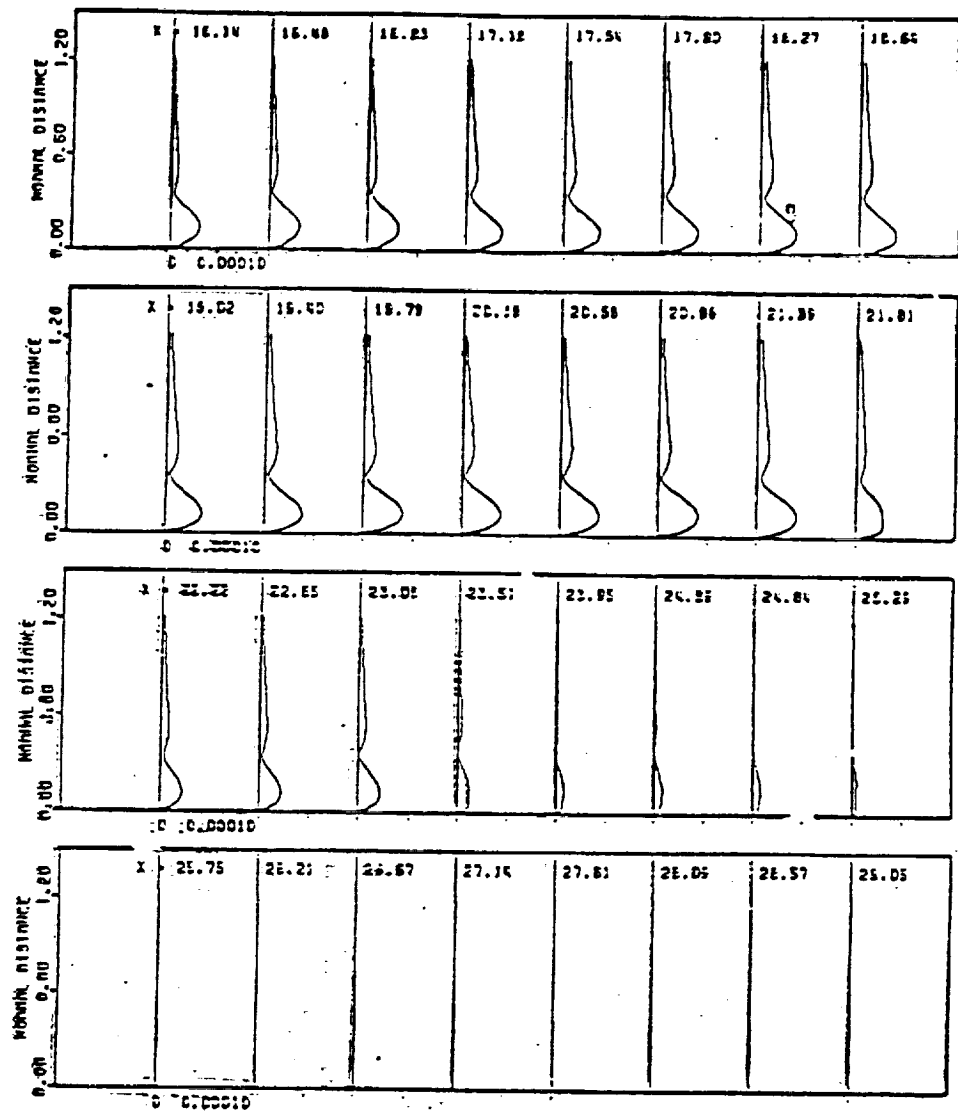
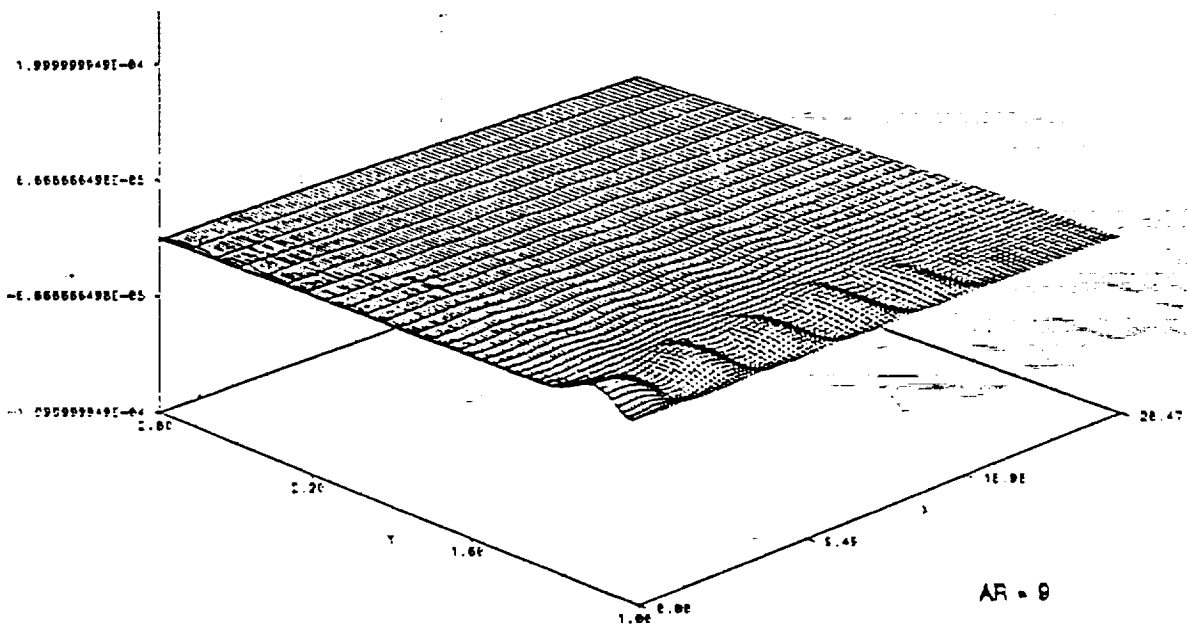
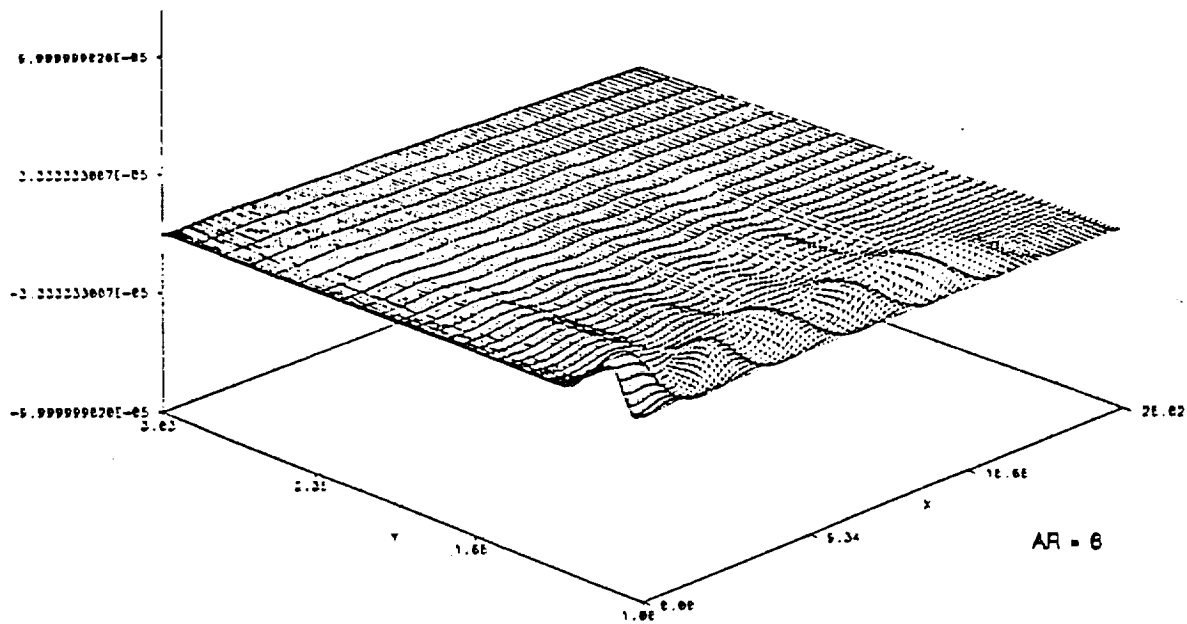
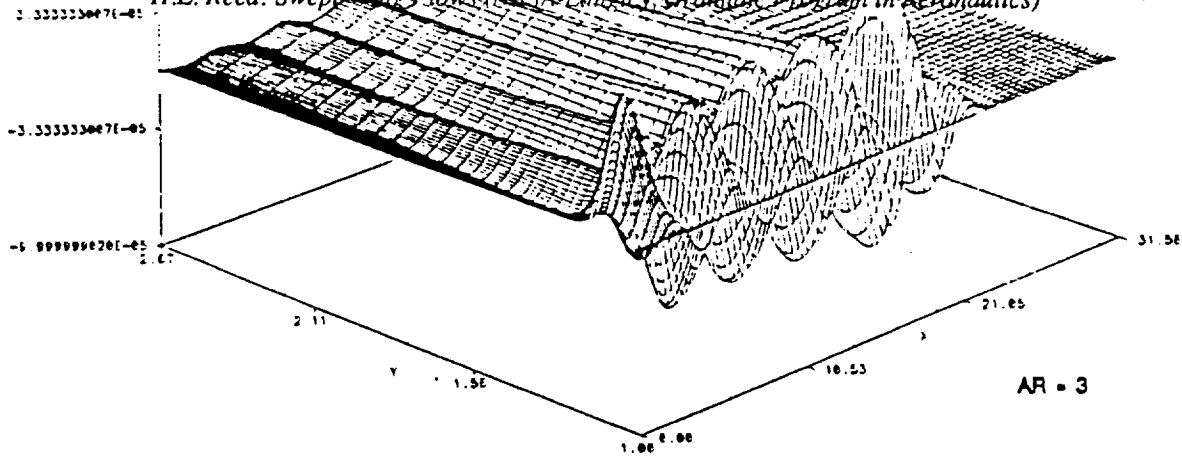


Figure 19 cont.



max. amplitude ratio $0.80 = \frac{u'_{TS}}{a_s}$
 $\lambda_{TS} = 4.5$

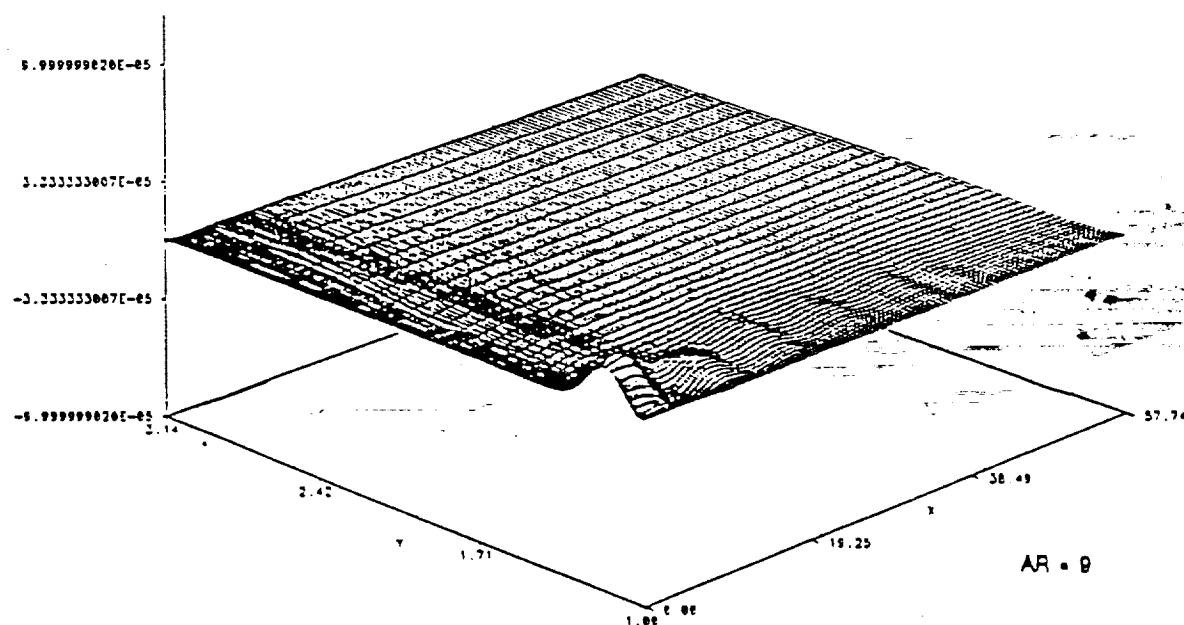
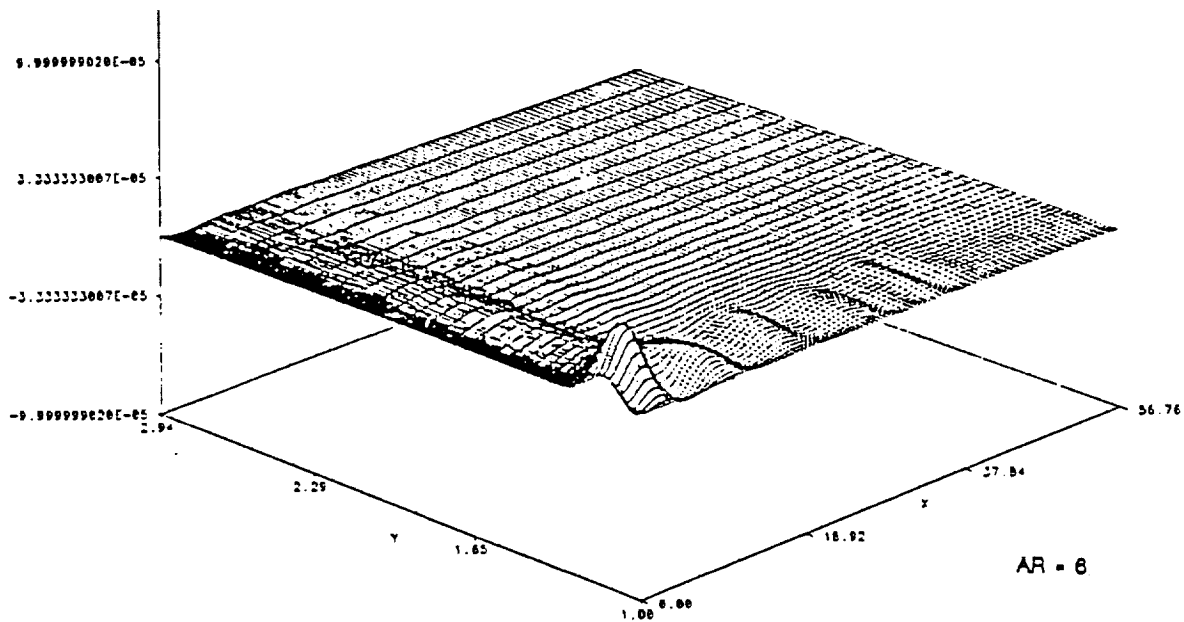
Figure 19 cont.



$F = 230$

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Figure 20



F = 110

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Figure 21

surface shape of the AR=6 leading edge

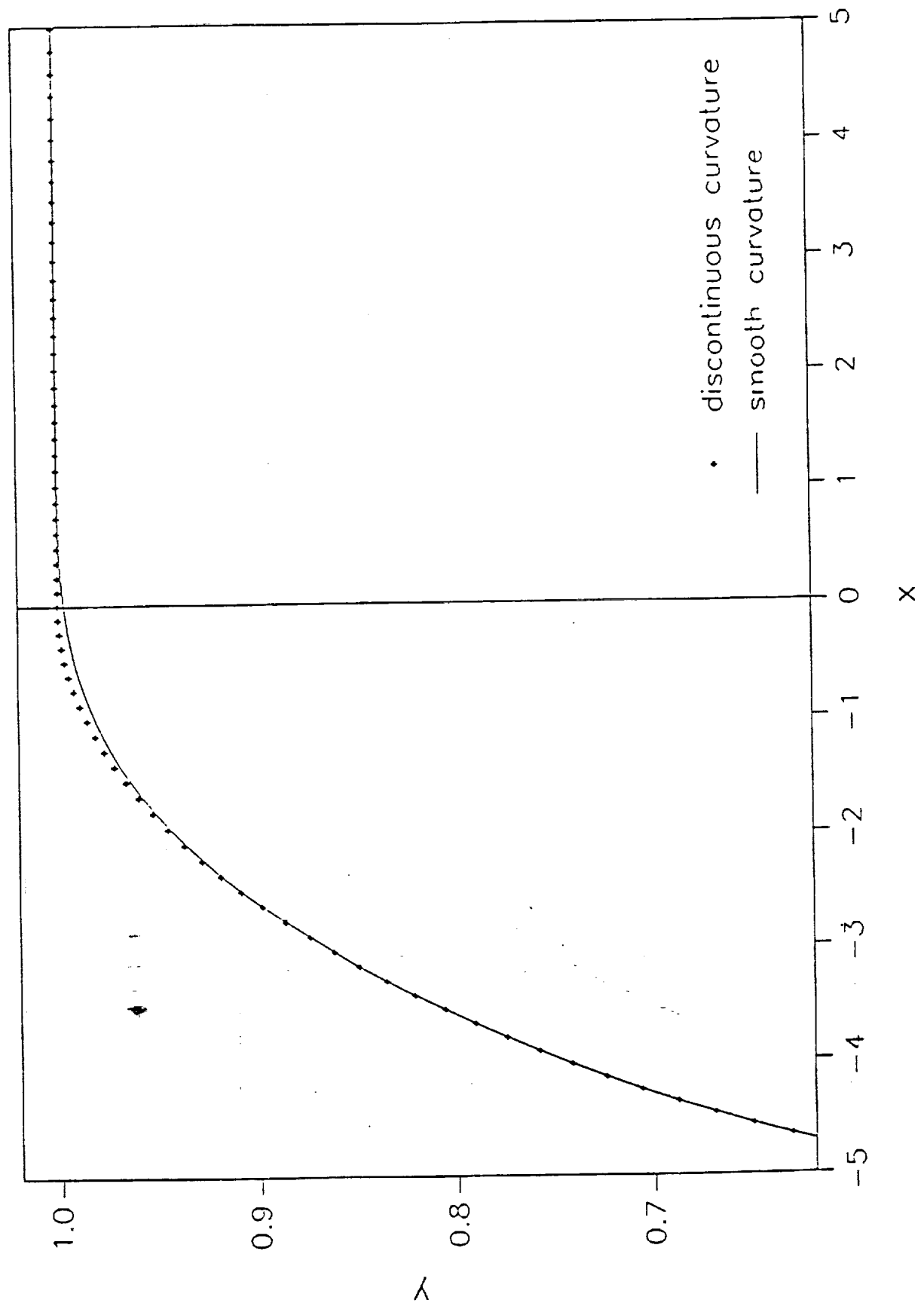


Figure 22

Variation of curvature for AR=6 leading edge

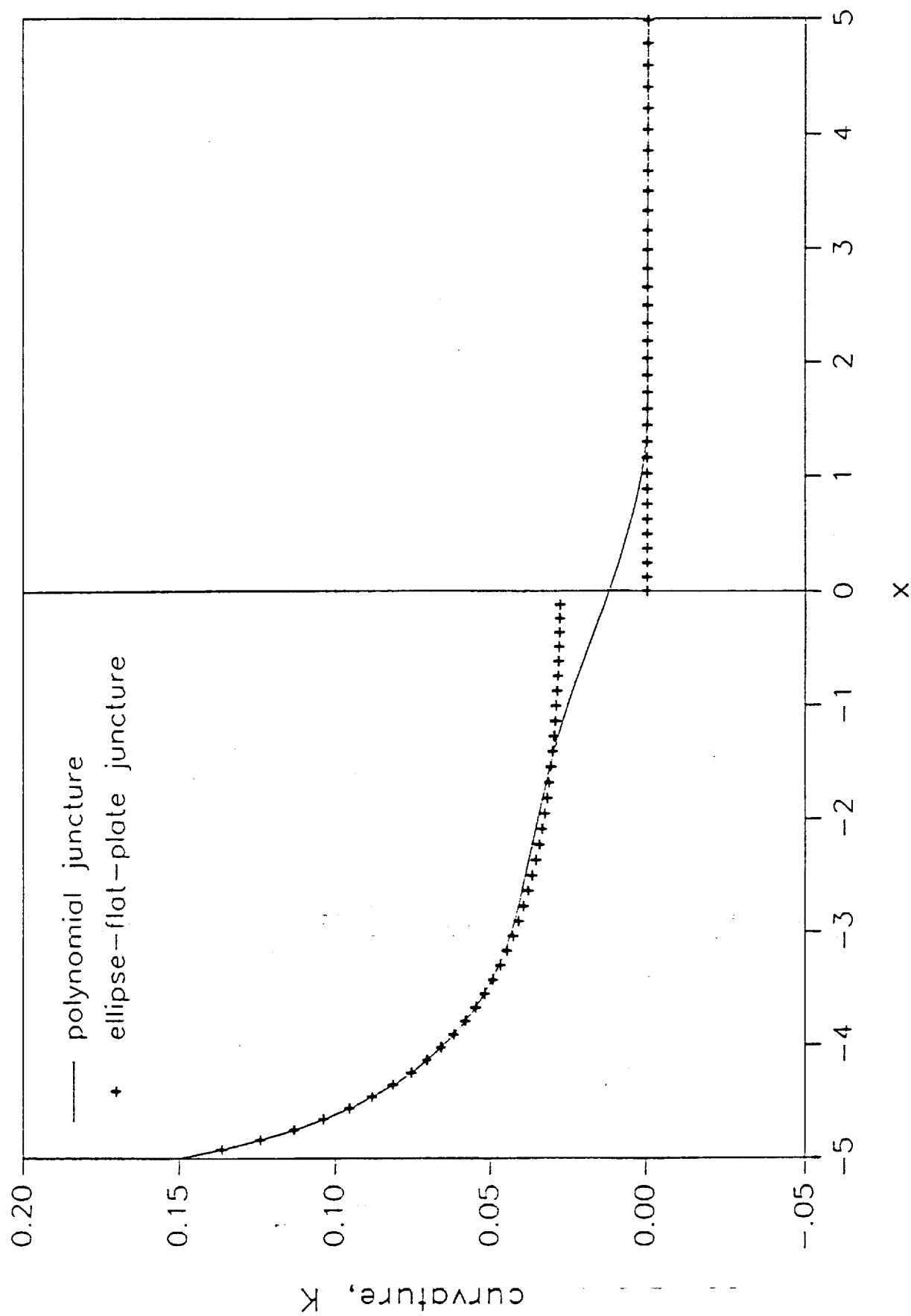


Figure 23

Basic-state (steady) pressure gradient along the wall

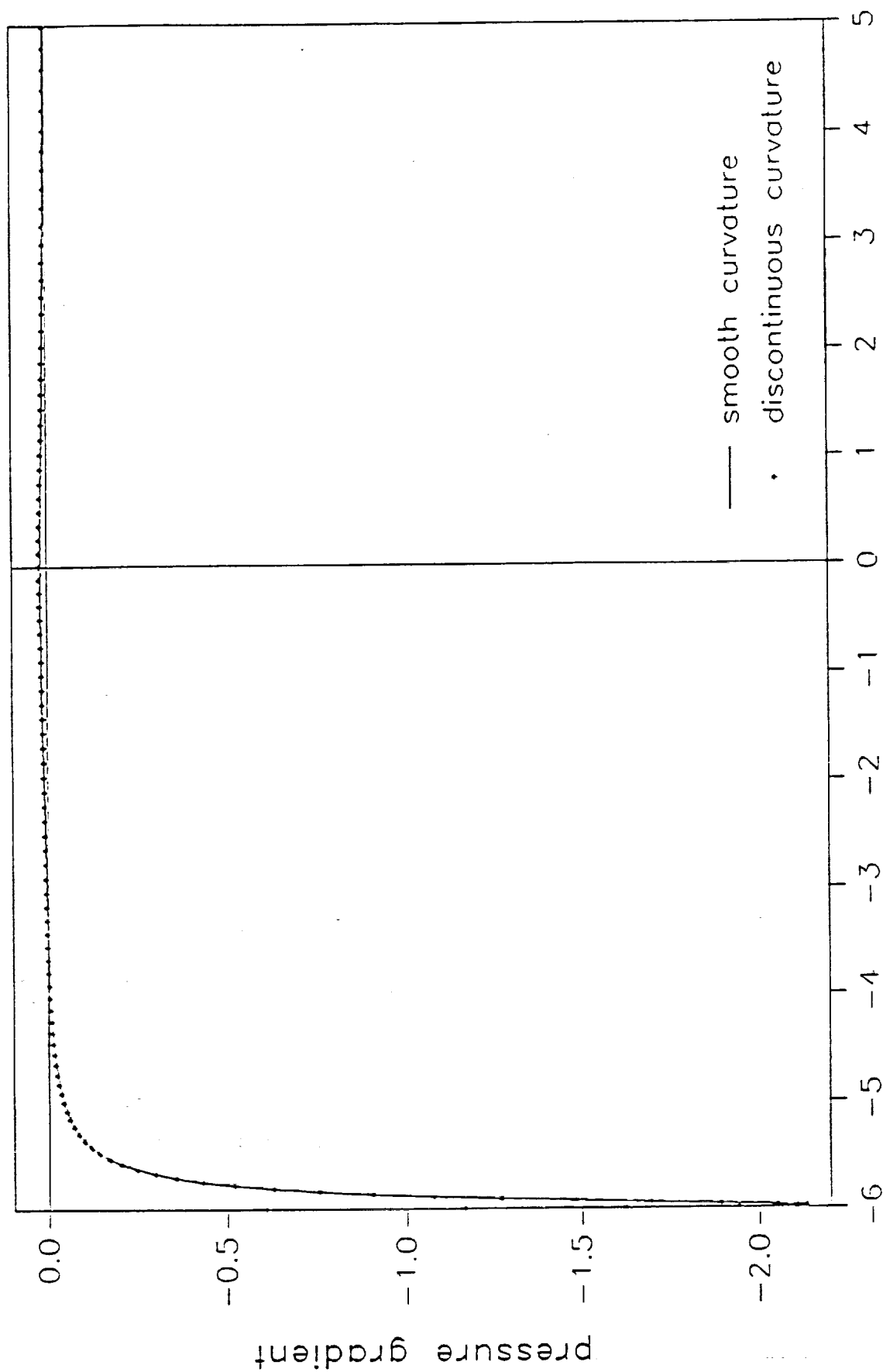


Figure 24

Basic-state (steady) pressure gradient along the wall

AR=6, RE=2400

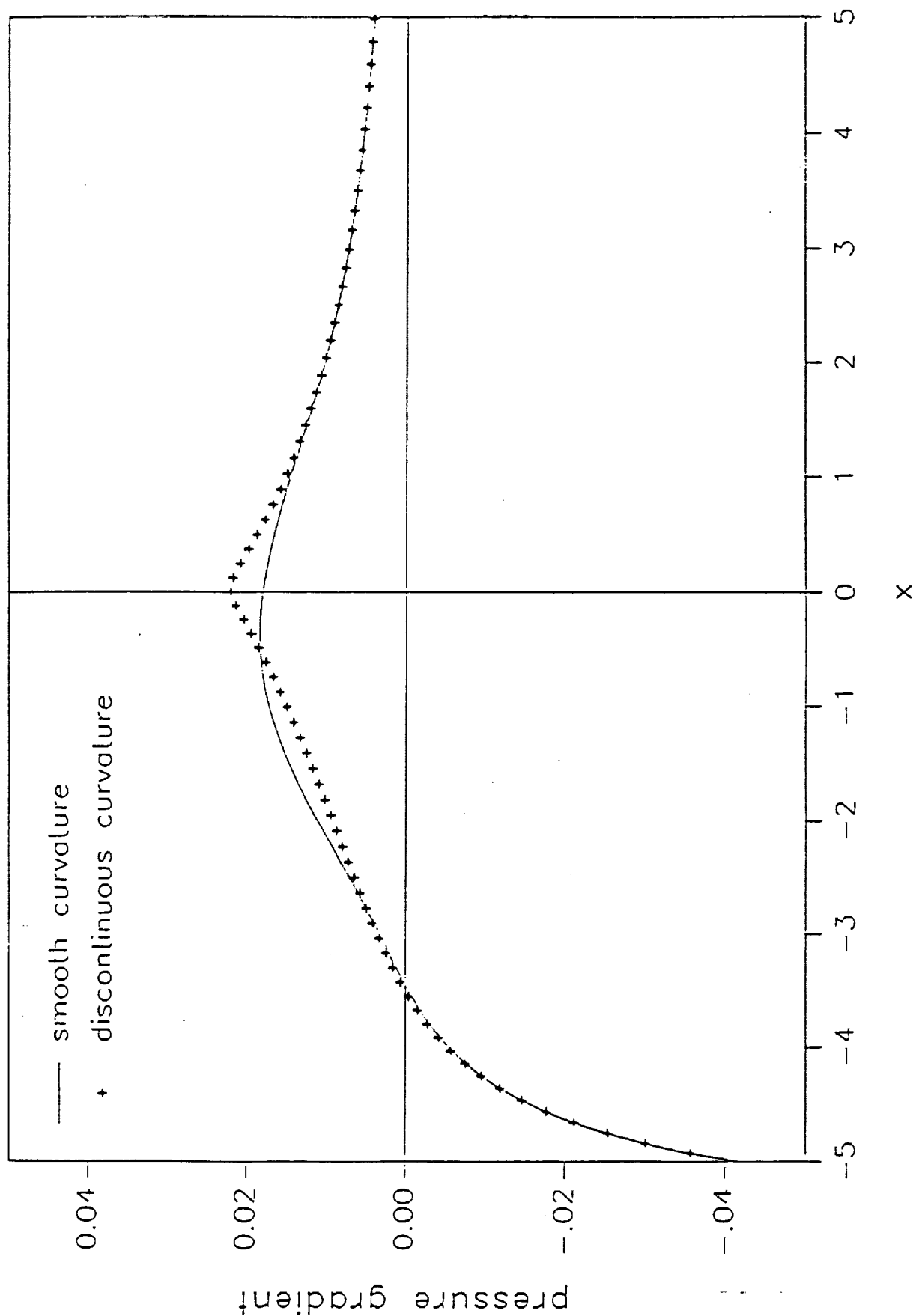


Figure 25

disturbance vorticity along the wall

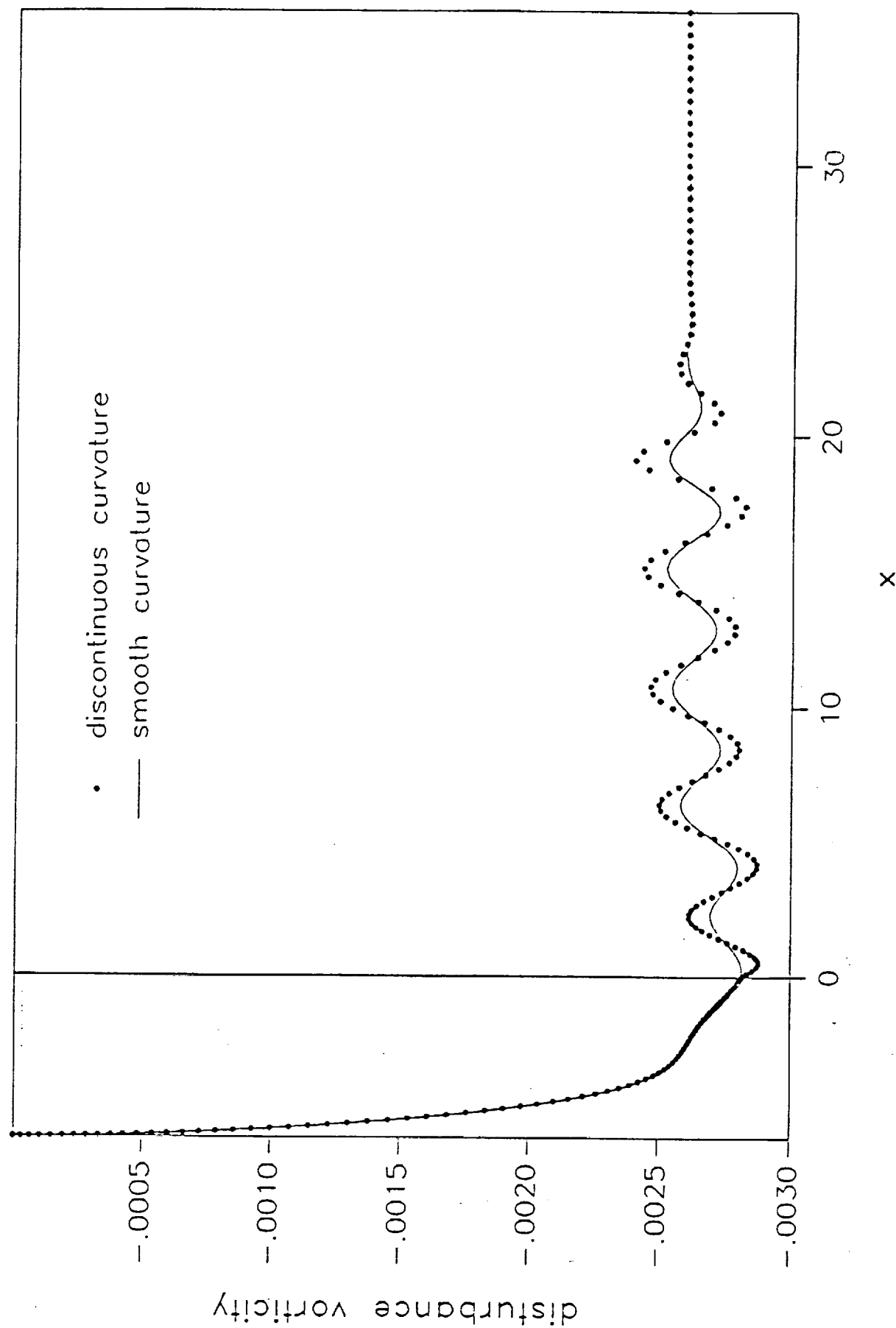
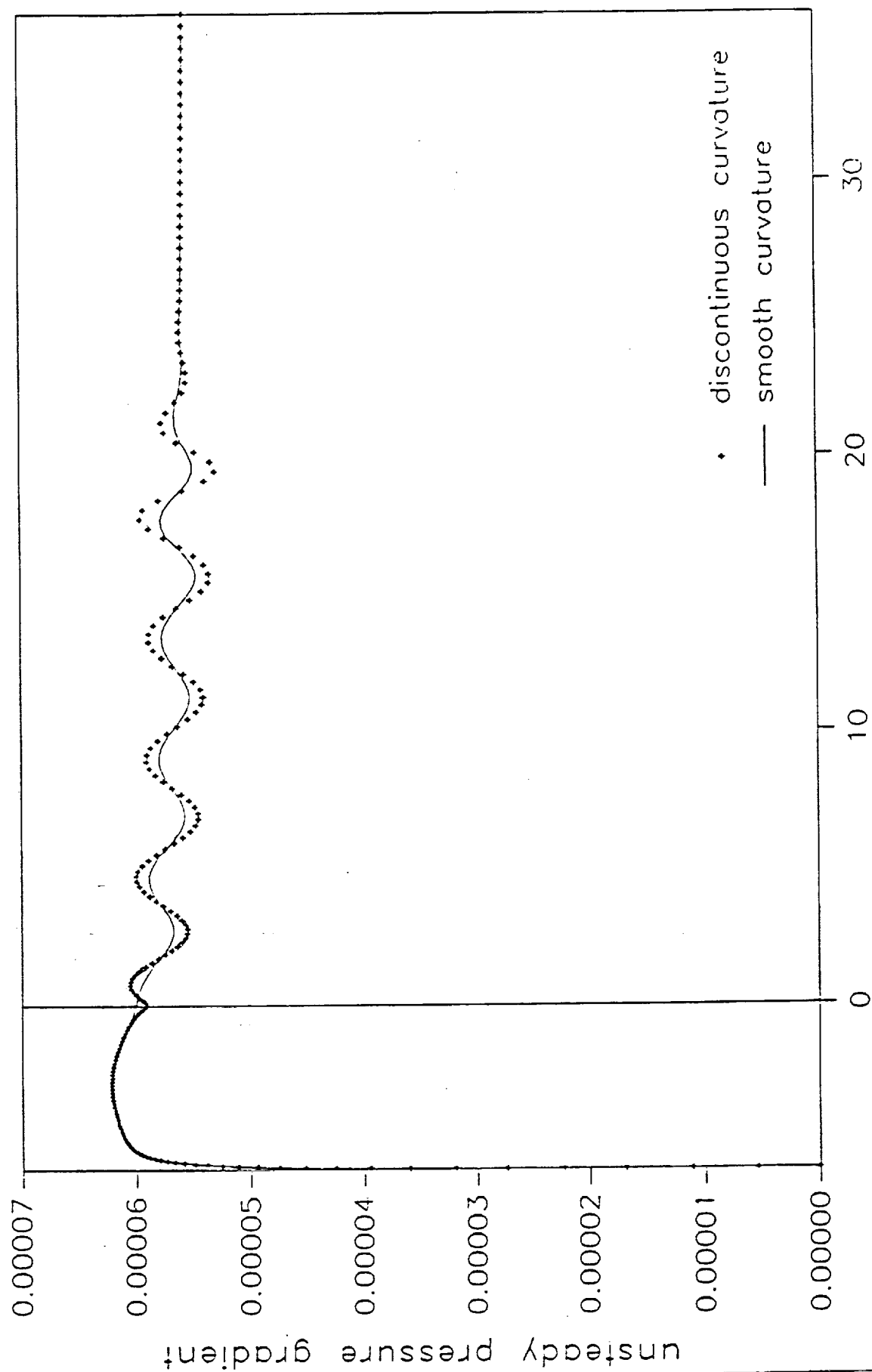


Figure 26

disturbance (unsteady) pressure gradient along the wall

AR=6, RE=2400, F=230



x

Figure 27

Instantaneous Disturbance Streamlines
 $Re=3$, $f=230$, after 4 cycles

CONTOUR LEVELS

-.17000
 -.03450
 -.03400
 -.03200
 -.03000
 -.02800
 -.02600
 -.02400
 -.02200
 -.02000
 -.01800
 -.01600
 -.01400
 -.01200
 -.01000
 -.00800
 -.00600
 -.00400
 -.00200
 0.00000
 0.00200
 0.00400
 0.00600
 0.00800
 0.01000
 0.01200

0.000
 0.00 DEG
 2.40x10**3
 154x70
 VACH
 ALPHA
 Re
 GRID

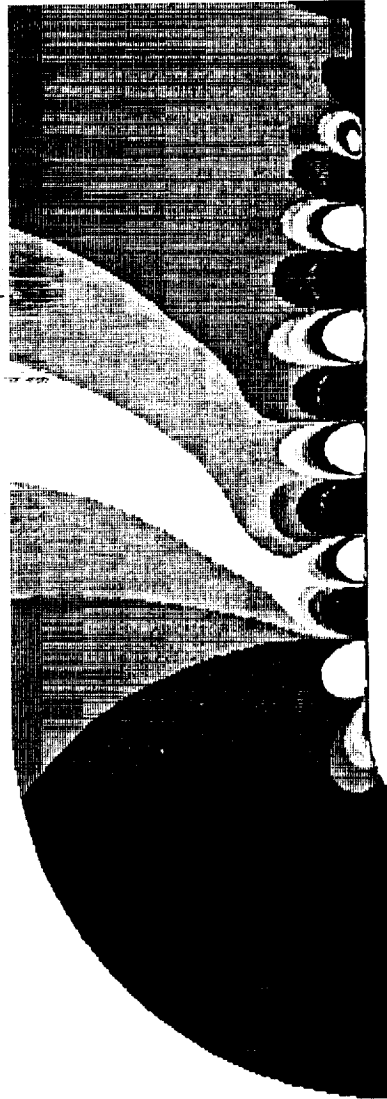


Figure 28

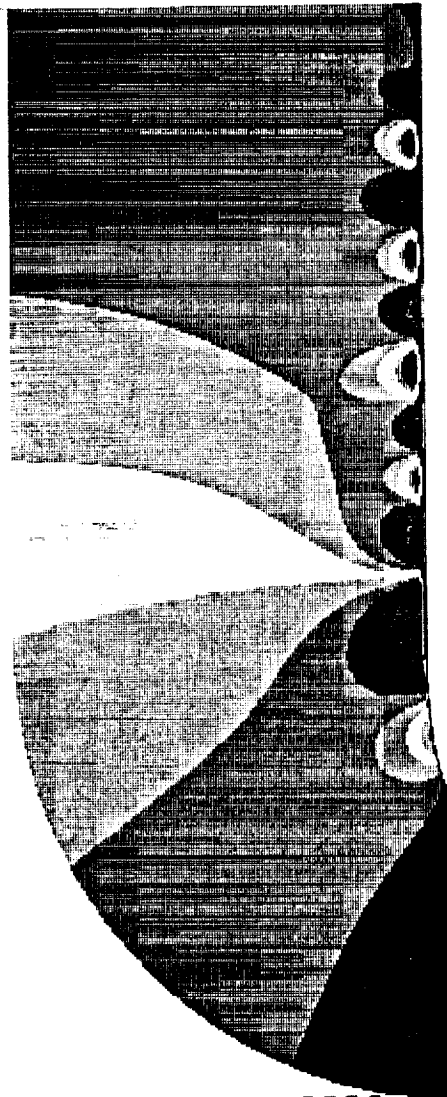
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Instantaneous Disturbance Streamlines
 AR=6, F=230, after 4 cycles

CONTOUR LEVELS

0.000 MACH
 0.00 DEG ALPHA
 2.40x10⁻³ Re
 170x70 GRID

-.03400
 -.03200
 -.03000
 -.02800
 -.02600
 -.02400
 -.02200
 -.02000
 -.01800
 -.01600
 -.01400
 -.01200
 -.01000
 -.00800
 -.00600
 -.00400
 -.00200
 0.00000
 0.00200
 0.00400
 0.00600
 0.00800
 0.01000
 0.01200



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Figure 29

Instantaneous Disturbance Streamlines
 $Re=6$, $f=230$, continuous curvature

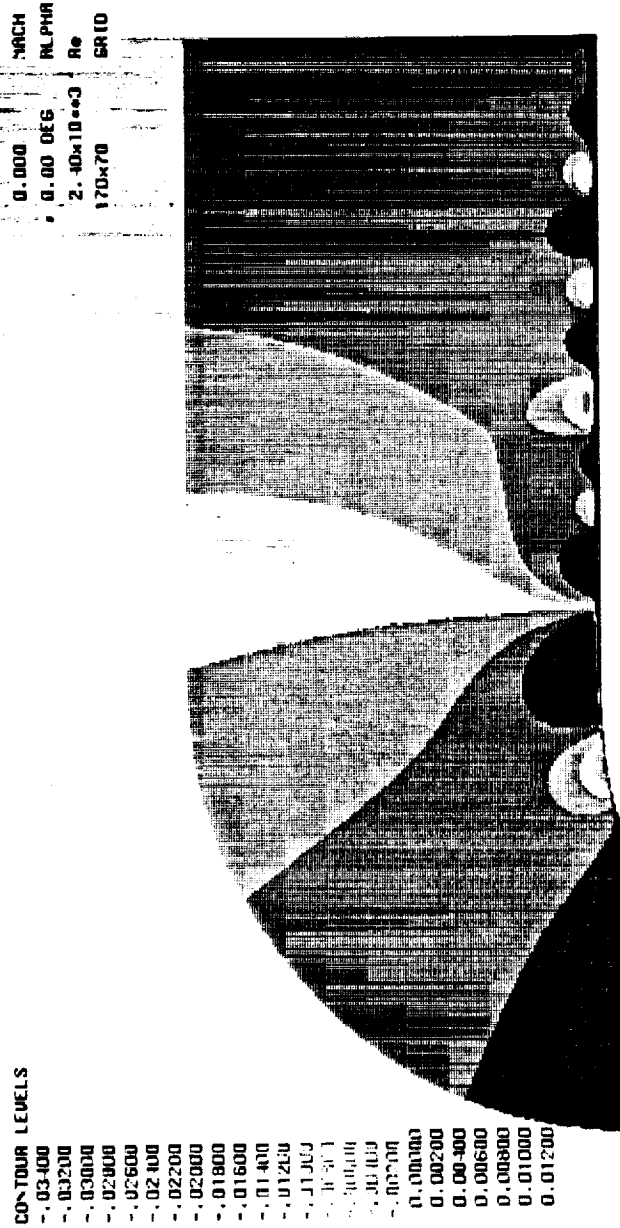


Figure 30

Instantaneous Disturbance Streamlines
 $Re=9$, $f=230$, after 4 cycles

CONTOUR LEVELS

-0.03400
 -0.03200
 -0.03000
 -0.02800
 -0.02600
 -0.02400
 -0.02200
 -0.02000
 -0.01800
 -0.01600
 -0.01400
 -0.01200
 -0.01000
 -0.00800
 -0.00600
 -0.00400
 -0.00200
 0.00000
 0.00200
 0.00400
 0.00600
 0.00800
 0.01000
 0.01200

0.000 YACH
 0.00 DEG ALPHA
 2.40x10⁻³ Re
 165x70 GR10



Figure 31

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APPENDIX I. Resume of H.L. Reed

Arizona State University

HELEN LOUISE REED

Associate Professor, Mechanical and Aerospace Engineering

EDUCATION

PhD VPI & SU, Dec. 1981
MS VPI & SU, June 1980
AB Goucher College, May 1977

EXPERIENCE

Aug 1985- present, Associate Professor, Arizona State University, Mechanical and Aerospace Engineering.
Sept 82-Aug 85 Assistant Professor, Stanford University, Mechanical Engineering.
Jan-Aug 82 Assistant Professor (Non-tenure track), VPI & SU, Engineering Science and Mechanics.
June 79-Dec 81 Graduate Research Assistant, VPI & SU, Engineering Science and Mechanics
June 77-June 79 Aerospace Technologist, NASA-Langley
July -Aug 84 Aircraft Energy Efficiency Office (ACEE), NASA-Langley Research Center, Hampton, VA
July -Aug 83 Summer University Faculty, Applied Mathematics Division, Sandia National Laboratories, Albuquerque, NM

CONSULTING

International Consultants in Science and Technology, Inc.; ICASE Consultant, NASA/Langley Research Center; Pratt and Whitney

SCIENTIFIC AND PROFESSIONAL SOCIETIES:

Member, American Academy of Mechanics	Associate Fellow, Amer. Inst. Aeronautics and Astronautics (AIAA)
Member, American Physical Society (APS)	Member, American Society for Engineering Education (ASEE)
Assoc. Member, American Society of Mechanical Engineers (ASME)	Member, Int'l Assoc. for Computational Mechanics (IACM)
Member, Mathematical Association of America (MAA)	Member, Sigma Xi
Member, Society for Industrial and Applied Mathematics (SIAM)	

SERVICE TO THE PROFESSION

Associate Editor, *Annual Review of Fluid Mechanics*, 1986-Present.
Technical Chair, *AIAA 19th Fluid, Plasma Dynamics, and Lasers Conference*, June 1987.
Co-Chair, *44th Annual Physical Society/Division of Fluid Dynamics*, Scottsdale, Nov. 1991.
Originator, *Annual Picture Gallery of Fluid Motions* at annual meetings of the APS.
Member, *U.S. Transition Study Group* under the direction of Eli Reshotko, 1984-Present.
Member, National Academy of Sciences/National Research Council *Aerodynamics Panel* which is a part of the *Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems*, 1990-1992.
Member, *Pres. Young Investigator Workshop on U.S. Engrg. Math. and Science Education for the Year 2010 and Beyond*, Wash. DC, 1990.
Member, *AIAA Technical Committee on Fluid Dynamics*, 1984-1989.
Member, *Fluid Mechanics Technical Committee* of the *Applied Mechanics Division of the ASME*, 1984-Present.
Member, Steering Committee for *National Fluid Dynamics Conference*, June 1988-Present.
Univ. Representative, *NSF Fluids Engineering Workshop*. Group Leader/Coordinator of final document for Unsteady Flow Panel, 1986.
Chair, *ASME Junior Awards Committee* 1989-Present. Vice-Chair 1987-1988.
Member, Scientific Committee of 1992-3 IUTAM Symposium on *Nonlinear Stability of Nonparallel Flows*, Jan. 1990-Present.
Chair, *2nd Arizona Fluid Mechanics Conference*, Arizona State University, Apr. 4-5, 1986.
Organizer, *Transition Simulation Olympics* to be held at *National Fluid Dynamics Conference*, Summer 1992.
Co-Organizer, *Transition Symposium*, to be held at the *First Joint ASME/JSME Fluids Engineering Conference*, Portland, June 23-26, 1991.
Chair of 19 technical sessions at various conferences and symposia.

HONORS AND RECOGNITIONS

Phi Kappa Phi	Cunningham Fellowship Award from VPI & SU, 1981
Phi Beta Kappa	Presidential Young Investigator Award, NSF, 1984
Merit Scholarship from the State of Maryland, 1974	AIAA Excellence in Teaching Award, Arizona State University, F88
Recipient of a NASA fellowship, 1976	Professor of the Year, Pi Tau Sigma, Arizona State University, 88-89
Outstanding Summer Employee Award from NASA-Langley, 1976	Associate Fellow, AIAA, Dec. 1990
Torrey Award for Excellence in Mathematics, Goucher College, 1977	
Outstanding Achievement Award from NASA-Langley, 1978	

PRINCIPAL PUBLICATIONS AND PAPERS

- A.H. Nayfeh, H.L. Reed, S.A. Ragab, "Flow over Plates with Suction through Porous Strips," *AIAA J.*, **20**, 5, 587, May 1982.
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